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Effort Flow Analysis: A Methodology for Directed Product Evolution Using Rigid Body and Compliant Mechanisms

Publication No.____________

James LaMonte Greer, PhD
The University of Texas at Austin, 2002

Supervisor: Kristin L. Wood

This dissertation presents a systematic design methodology for directed product evolution that uses both rigid body and compliant mechanisms to facilitate component combination in the domain of mechanical products. The methodology, known as effort flow analysis, is based on fundamental tenets from the Theory of Mechanics, and Graph Theory. Effort flow analysis uses a semantic network known as an effort flow diagram to model a product as a connected set of nodes and links. The nodes represent the components of the product and the links represent the interfaces between the components. The effort flow diagram is a quasi-static model of the flow of effort (force or torque in the mechanical domain) as it transits the body from input to output. In order to capture the effect of the relative motion that occurs at the interfaces, a basis set for relative motion is developed for effort flow analysis. The basis consists of 4 possible link type cases, (1) No relative motion at the interface or away from the interface, (2) Component relative motion that occurs away from the interface, (3) general Relative motion between components, and (4) Interface relative motion that occurs only at the interface. These are known as N-Links, C-Links, R-Links, and I-Links respectively. Rigid body combinations are sought for components connected by N-Links and compliant mechanism combinations are sought for components connected by the other link types. Component combination opportunities are sought based on the connection structure of the effort flow

diagram. Guidance for component combination is captured in a set of 29 product-evolution guidelines that are derived from the results of an empirical study. In addition, an example solution is cataloged for each of the guidelines to foster design-by-analogy efforts by the designer. Finally, the work presents a novel design and prototype for a compliant one-piece umbrella frame, which serves as a proof of concept for the methodology. Possible future pursuits are presented in the areas of knowledge capture using guidelines and solution examples. In addition, the possibility of a function-to-component matrix for automated concept generation is considered.

The Dissertation Committee for James LaMonte Greer Certifies that this is the approved version of the following dissertation:

Effort Flow Analysis: A Methodology for Directed Product Evolution Using Rigid Body and Compliant Mechanisms

Committee:

Kristin L. Wood, Supervisor

Joseph J. Beaman

Richard H. Crawford

Daniel D. Jensen

Matthew I. Campbell

Effort Flow Analysis: A Methodology for Directed Product Evolution Using Rigid Body and Compliant Mechanisms

by

James LaMonte Greer, BSME, MSME

Dissertation
Presented to the Faculty of the Graduate School of
The University of Texas at Austin
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for the Degree of

Doctor of Philosophy

The University of Texas at Austin
August 2002

Dedication

To all those who believed in me… even when I didn't.

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Chapter 1 - Introduction to Effort Flow Analysis

Currently, product evolution progresses naturally and somewhat randomly over the life cycle of a product. A product idea is conceived and given life through the creative process of design, the result of which is the embodiment of a physical artifact that is offered to customers in exchange for something of value, typically money. Market pressures due to competition dictate that over time the product must increase its performance and improve its functionality. The only way to improvement along these axes is to periodically redesign the product. The difficulty arises when one is faced with the question of how to move the product along its evolutionary path more quickly and efficiently than the competition. This need for efficient product evolution motivates the development of a directed evolution methodology for products in the mechanical domain.

1.1 - Product Development is Product Evolution

The motivation for this work stems from the fundamental goal of product development, which is to create a product that satisfies the needs of a customer. There is an initial period when a new or innovative product can satisfy the customer with minimal product evolution effort. However, as time passes, customers come to demand more and the product must change to meet the new needs. The Theory of Inventive Problem Solving (TIPS) suggests that products follow a life cycle of birth, growth, maturity, and decline, or more simply, products evolve [1]. When viewed in the broader scientific context, evolution is the study of variation and selection.

Though not strictly equivalent to one another, product evolution may be thought of as being analogous to Darwin's theory of Natural Selection. The crux of Darwin's theory is that survival in the struggle for existence is not random, but depends on the hereditary constitution of the surviving individuals [2]. This unequal ability of individuals to survive and reproduce will lead to a gradual change in a population with favorable characteristics accumulating over generations. Darwin's theory provides us with a familiar frame of reference for the treatment of engineered products. In engineered products, evolution equates to the favorable features and functions of a product being maintained and propagated, while the undesirable traits are diminished.

Hence, classes of products tend to evolve toward higher and higher levels of desirable features while exhibiting a reduced number of undesirable traits [3]. Pressures from the market place, such as changing customer needs and expectations, shareholder satisfaction, competitive pressures, and economic climate provide the underlying motivation for product evolution. One of the key elements in keeping a product viable is identification of the desirable and undesirable features within the product and within the products of competitors. In general, this goal is achieved by understanding the needs and wants of the customers and by understanding the technical aspects of providing the product.

This discussion begs the question why undesirable features exist at all. One reason for their existence is the resolution of the conflicts or tradeoffs that arise while designing. Thus, the creation of a desirable feature leads to the instantiation of undesirable features as a byproduct. An understanding of conflicts and tradeoffs is required before action can be taken to ameliorate the difficulty. In the context of product design, this conflict reduction effort occurs at the behest of the design engineer through the application of systematic design methodologies. Systematic design methodologies are the application of best practices in the science of design, and cover a wide range of applications. In taking a product through the evolutionary process, the current instantiation of the product must be analyzed and understood according to its functions, its technology, its strengths, and its weaknesses. Many proposed methodologies result in mechanisms of product evolution; several of which are widely used today. Samplings of the methodologies that affect product evolution are treated below.

<u>Theory of Inventive Problem Solving</u>: The theory of inventive problem solving (TIPS) is the result of an empirical observation of over two million patents to determine how products evolve. According to the TIPS, the evolution of engineered systems develops according to the same patterns, independent of the engineering discipline or product domain [4, 5]. These patterns may be used to predict the trends of future evolutions in a product domain. They may also be used to direct the search for new concepts [1].

Design For Manufacturability: DFM is a set of methods and approaches by which the manufacturability of industrial products can be "optimized" during the product development process [6].

Design For Assembly: DFA is a simple, structured analysis technique which gives design teams the information they need to reduce product costs by: reducing the number of parts, optimizing manufacturing processes, simplifying parts handling, and improving product assembly [6].

Design For eXcellence: DFX is an overarching approach where all desirable characteristics are maximized. The desirable characteristics, according to Bralla [7], are: Function and performance, Safety, Long-term quality, Manufacturability (including assemblability), Environmental friendliness, Serviceability, User friendliness, Appearance, Features, and Short time to market.

Product Architecting: Product architecting is the process where functional ideas begin to incur spatial effects, and specific configurations are selected among the many possible workable solutions [8]. In this process, the development of modularity and the physical interfaces of the product have dramatic effects on many areas of product performance [9].

Axiomatic Design: The two fundamental design axioms given by Suh [10] are briefly summarized as the Independence Axiom, which states that the independence of the functional requirements should be maintained; and the Information Axiom, which states that the information content should be minimized. Achievement of these goals over successive design iterations implies evolutionary improvement of the product.

In reviewing the methodologies discussed above, one of the many questions that come to mind is, "How does one measure the evolutionary progress?" Product evolution does not seem to have a generally accepted norm for its measurement. The motivation for measurement of evolution is to allow an enterprise to assess its position relative to its competition. Understanding the degree of advantage or disadvantage can be a valuable tool in deciding how to allocate resources for product evolution efforts. One measure that may be useful in comparing the product evolution state of competitive products is the complexity of the artifacts. As products evolve, the complexity for a given level of functionality tends to decrease. Each of the product evolution methodologies discussed

ultimately seeks to drive a product toward reduced complexity. This leads to the conclusion that product design and redesign leads to product evolution through complexity reduction. The use of complexity as a measure of product evolution begs the further question, "How is complexity measured?"

1.2 - COMPLEXITY REDUCTION

The definition of complexity as used in engineering design is not a clearly defined term. Webster [11] defines complexity as: "The quality or state of being complex," and defines 'complex' as: "**2:** Hard to separate, analyze, or solve." In science and engineering, the definition of complexity has itself been a complex problem. According to Hinckley [12], product complexity has two parts: the number of elements, and the difficulty of generating those elements, or more generally as complexity due to *quantity* and complexity due to *difficulty*.

According to Suh [10], those in manufacturing define complexity in terms of the amount of effort required to produce a product. Practitioners from the field of computer science use the term 'algorithmic complexity,' which is concerned with the number of lines of computer code necessary to achieve a desired result [13]. Computer program length indicates the complexity of the task; short programs for less complex tasks and longer programs for more complex tasks. A further refinement of this approach uses two classes of complexity measures, static and dynamic. A static complexity measure is simply the minimum number approach discussed previously, while a dynamic complexity measure takes into account the algorithm and the inputs to the algorithm resulting in a complexity measure that is based on behavior [14].

In the mechanical design domain, Boothroyd *et al,* [6] characterize part complexity as the number of features that must be created in the part during the manufacturing process. For example, when determining the relative complexity for the mold surfaces of an injection-molded part, the number of sudden changes in the slope or curvature of the mold cavity surface and the number of holes or depressions are counted. A complexity rating is then calculated using the relationship:

$$X_C = 0.01N_{sp} + 0.04N_{hd} \tag{1.1}$$

where

N_{sp} = number of surface patches

N_{hd} = number of holes or depressions

It is interesting to note that the relative complexity of the mold, and thus the part, is a combination of the number of features as well as the difficulty of creating those features as evidenced by the relatively greater weight given to holes and depressions compared to surface patches. This observation fits nicely with Hinckley's assertion that any valid measure of complexity must have two essential elements, a quantity measure and a difficulty measure. Hinkley's definition for the two elements of complexity is:

> A quantity measure – identifies the number of elements that contribute to complexity.
>
> A difficulty measure – measures the relative difficulty in generating or executing each of the elements.

Equation (1.1) makes use of the fact that it is relatively easy to determine the quantity measures in the form of the number of features. The difficulty measure, on the other hand, is generally harder to quantify. For example, in the case of Equation (1.1), the relative weights were developed from an empirical study of a large number of molds from different applications domains [6, 15]. Hence, the difficulty measure in this approach requires that many effects be considered.

Suh [16] proposes a definition of complexity for design that is based upon probability and information theory: "*complexity is defined as a measure of uncertainty in achieving the specified functional requirements.*" Suh's definition is consistent with the definitions discussed thus far; for example, a product with many parts is thought to be more complex than a product with few parts. The higher complexity is because the uncertainty of satisfying the functional requirements increases with the number of parts used to satisfy those functional requirements due to increased opportunity for defects or failure. Additionally, the more difficult the process used to produce a functional requirement, the more uncertain the outcome of the process.

A more easily applied complexity metric for the mechanical design domain is proposed by Hoult and Meador [17]. This method uses information theory to calculate the relative complexity of a part or assembly of parts:

$$I = \sum_{i=1}^{N} Log_2\left(\frac{\text{dimension}_i}{\text{tolerance}_i}\right)\text{bits.} \tag{1.2}$$

Here, complexity is related to the sum of the information content of the engineering drawings based on the dimensions and tolerances. This result is predicated on the use of standard practices in engineering drawing such that the minimum number of dimensions is used to completely describe the artifact. Once again, the theme of quantity and difficulty arises in the complexity metric of Equation 1.2. The dimension represents the quantity measure, while the tolerance represents the difficulty measure. As the dimension increases so does the quantity, and as the tolerance is made tighter, the difficulty of achieving the desired result is increased. Hoult and Meador report that the cost estimates for machined components generated using this method are as good as detailed estimates done in the traditional manner by an experienced estimator. The measurement of complexity using the quantity and difficulty measures is a consistent theme throughout the techniques presented thus far, yet no single measure of product complexity has been universally accepted in the literature.

One measure that may indirectly indicate the relative complexity between a given set of products or designs is the cost of manufacturing. Two design methods presently available for predicting and analyzing production issues are Design for Manufacturability (DFM) and Design for Assembly (DFA). One of the most comprehensive implementations of these two design tools is known as Design For Manufacturing and Assembly (DFMA).

1.3 - Design For Manufacturing and Assembly (DFMA)

The cost of producing a product is of key concern in business. It has often been stated that as much as 80% of the total life cycle costs are fixed during the preliminary stages of product design, and that 40% of those costs are associated with assembly [18-

20]. In light of this fact, DFMA has emerged as one of the dominant approaches to reducing manufacturing and assembly costs and has spawned various design methods commonly referred to as "Design For X" [7]. The DFMA method presented by Boothroyd, Dewhurst and Knight [6] suggests that reducing the number of parts, materials, and/or processes within a product can reduce product costs. Focusing on assembly, this approach suggests that there are two main cost drivers:

(i) the number of parts in the product or subassembly, and

(ii) the ease of handling, insertion and fastening the parts.

The first cost driver ultimately leads the designer to seek the minimum number of parts that will satisfy the desired functional requirements of the product. In DFMA, this is known as the theoretical minimum number of parts. The theoretical minimum number of parts represents the least number of components that could conceivably be used to satisfy the functional requirements of the product. To arrive at this minimum result, three part combination criteria are applied. [6]

> "...the theoretical minimum number of parts represents an ideal situation where separate parts are combined into a single part unless, as each part is added to the assembly, one of the following criteria is met:
>
> The part moves relative to all other parts already assembled during the normal operating mode of the final product. (Small motions which can be accommodated by elastic hinges do not qualify.)
>
> The part must be of a different material than, or must be isolated from, all other parts assembled (for insulation, electrical isolation, vibration damping, etc.).
>
> The part must be separate from all other assembled parts, otherwise assembly, or parts meeting one of the above criteria would be prevented."

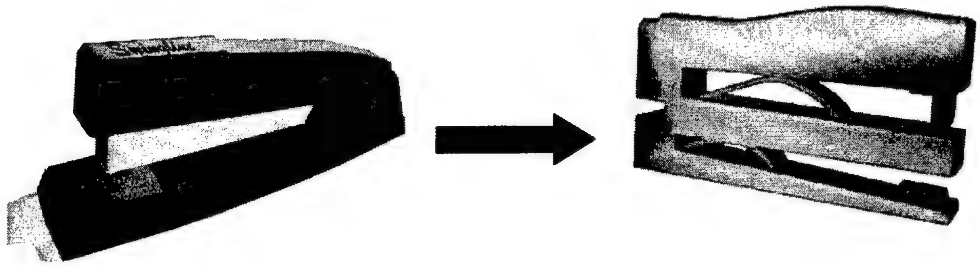


Figure 1.1: Desktop Stapler Evolution [21]

Designers using these guidelines have pursued opportunities for component combination in very creative ways resulting in some interesting devices [22, 23]. One example is the evolution of a desktop stapler shown in Figure 1.1. The stapler on the right, designed by Ananthasuresh and Saggere [24] exhibits the extreme application of the component combination strategy for product evolution.

As a strategy, part combination decreases the number of parts that compose a product while maintaining essential functionality. Piece count reduction in many cases is the most effective means of improving assemblability. Fewer parts usually imply fewer operations, less handling, and quicker assembly (besides special cases identified by Hinckley [12]). Piece reduction has broader implications as well, for example, Douglas Commercial Aircraft Co. ran simulations to determine what drives the cost of their commercial airframe construction. They discovered that in addition to the costs of assembly, the costs of fabrication, quality assurance, overhead-inventory levels, tracking, and purchasing all depend on piece count [25]. In general, driving an artifact design toward the use of fewer components while continuing to provide the desired functionality is a drive to lower complexity with regard to both quantity and difficulty measures. If complexity is indeed a reasonable measure of product evolution, then the pursuit of part count reduction opportunities in fact drives an artifact toward higher levels of product evolution.

1.4 - COMPLIANT MECHANISMS

Within DFA, the specific area of part combination receives considerable attention. Part combination (sometimes called piece count reduction) is the combination of once separate parts into a single piece. Components having relative motion between

them were traditionally thought to be either un-combinable, or to require significant redesign if the combination of the parts is to be successful, but this limitation may not be necessary. Recently, examples in the area of "compliant" mechanisms have brought new focus to the combination of parts that experience relative motion. One proposal is that parts having relative motion can be combined into monolithic mechanical devices by using jointless compliant mechanisms [24].

The field of design research that concentrates on the creation of monolithic compliant mechanisms is known as Design for No Assembly, or DNA, in the popular literature [24, 26]. A commercially available DNA based device is known as a "ComPlier™" (Compliers Inc., Rolla, MO; Figure 1.2), which is a pair of pliers designed and constructed using compliant joints in place of the traditional kinematic joints [27].

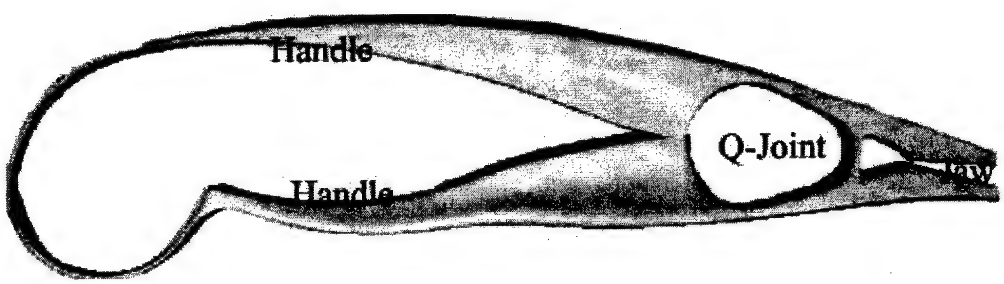


Figure 1.2: Compliant Pliers (ComPlier™)

This compliant mechanism, formed from a single piece of material, replaces an assembly of multiple components initially appearing to require relative motion to perform the product function(s). In this case, significant redesign effort and/or experience was needed to accomplish the part combination as the design of this mechanism required a departure from the original spatial layout of "components," or topology, of the multi-part device. However, it seems possible that complex products can be redesigned using the same topology and geometric features by replacing subsystems directly with compliant components. Creating monolithic compliant products requires a set of specialized tools for their design and synthesis.

Compliant mechanism design and synthesis falls into two distinct areas. These two areas are broadly distinguished by the approach taken in modeling the mechanism. The first class is based on modification of the rigid body model. For example, the pseudo rigid-body model by Howell [28-35]. In this approach to modeling, parametric changes are made to the rigid-body model to allow accurate modeling of the compliant mechanism behavior using computational tools and techniques developed for rigid body analysis. More importantly, this approach may allow the designer to engage the intuition built with rigid body design in the design of compliant mechanisms.

The second class of compliant mechanism design and synthesis approaches is comprised of the topology optimization methods [36-45]. In this approach, a general topology for the compliant mechanism is defined, to include the input/output ports, constraint relations, forces and desired deflections. The general topology is optimized to minimize the strain energy in the resulting mechanism. The optimization is carried out using finite element analysis software operating within the loop of the optimization scheme. The elements are manipulated to simulate addition or removal of material until the optimum configuration is achieved.

Neither the rigid-body simplification approach nor the topology optimization approach to design and synthesis of compliant mechanisms contains a strategy for determining when and where to use compliant mechanisms in product design. Both approaches are brought to bear on the problem once a candidate for replacement has been identified. In the field of design science, these approaches are extremely useful tools for analysis, but are not especially useful as concept generation strategies.

Monolithic compliant products may represent the ultimate, albeit difficult to achieve, goal of complexity reduction, but the question remains whether taking this extreme approach is indeed complexity reduction. If the complexity is measure in terms of part count quantity, then the answer must be yes, but when factors such as mold costs and production quantities are considered the answer becomes less obvious. Such are the challenges and the motivation for research in the area of designing compliant mechanisms for piece count reduction in mechanical devices.

1.5 - Effort Flow Analysis

Effort flow analysis is a systematic design methodology for directed product evolution. Effort flow analysis is used to identify opportunities to improve the manufacturability and or assemblability of existing products through modeling and analysis of the individual components and their interactions [22, 46, 47]. Effort flow analysis focuses on the *mechanical* effort and motion interactions between components within a product highlighting opportunities to reduce part counts and complexity while encouraging function sharing. The mechanism used to direct product evolution in effort flow analysis is the design guideline. Where design guidelines are captured knowledge about specific artifacts or classes of artifacts. This places effort flow analysis squarely in the class of design methodologies that embody artifact theory.

It is the intention of this research effort to develop the fundamentals of effort flow analysis by addressing three key issues. The first issue is the need for a rigorous theoretical foundation to establish effort flow analysis as a legitimate product of engineering design research [48]. The second issue is to establish a substantial base of empirical observations to support broad application of the method [48]. The third issue is to ensure that the implementation of effort flow analysis is not constrained by the DFMA premises, especially the one stating that components cannot be combined unless there is limited or no relative motion between them. This DFMA principle receives special attention in effort flow analysis, and is intimately related to the overall motivation for developing *effort flow* analysis.

Effort flow analysis extends product evolution through component combination beyond the limitations of DFMA. With evolution of the method in mind, and in order to be consistent with current and future research efforts in this area, the term *effort flow* is used to describe the analysis methodology. Use of the term *effort* implies a broader class of physical phenomenon than does the term *force*. Hence, "Effort Flow" is used to indicate that the method may ultimately be applicable to a broader scope of products than those contained in the mechanical domain. This potential to evolve to other energy domains adds motivation for the development of a fundamental understanding of effort flow analysis in the mechanical domain in preparation for exploration in other domains.

1.6 - HYPOTHESIS AND OBJECTIVES

In this work, two hypotheses are addressed. The first hypothesis is that the application of effort flow analysis to a limited set of mechanical artifacts, carried out in the context of an empirical study, will lead to a number of product evolution guidelines that are themselves fundamental components of the effort flow analysis methodology. The second hypothesis builds upon the first and states that applying effort flow analysis, including the newly derived guidelines, to mechanical artifacts will lead to the synthesis of a significant number of evolved products. In particular, the artifacts evaluated in the study and those to which methodology are applied come from the domain of mechanical products whose scope is limited to those exhibiting relative motion based functions.

The primary objectives of this work is to create a comprehensive methodology for the directed evolution of products from the domain of mechanical effort transmitters. The outcomes targeted in support of this objective are as follows:

1. Formalize the theoretical foundations of effort flow analysis.
2. Develop a basis set of effort flow analysis design guidelines.
3. Conduct an empirical product study of existing designs.
4. Develop a matrix of design solutions that represent the results of applying the effort flow analysis methodology.
5. Develop a systematic approach to the synthesis of compliant solutions in product design.
6. Create a Personal Invention using the effort flow analysis methodology.

1.7 - ORGANIZATION

This dissertation is arranged to support the development of effort flow analysis as a directed product evolution methodology with a special emphasis on compliant mechanisms.

Chapter 2 provides an understanding of the prior art in the development of effort flow analysis. Chapter 3 establishes the theoretical foundations of effort flow analysis. The foundation is constructed from the theory of mechanics and the theory of graphs. Mechanics provides the physical relationships that are then represented using the Graph

Theory. Chapter 4 takes the background work presented in Chapter 2 and combines it with the foundation of Chapter 3 to develop the fundamental elements that form the effort flow analysis methodology. These elements include the importance of relative motion and its relationship to energy flow, the nomenclature of effort flow analysis, the relationship between effort flow analysis and the theory of technical systems, and finally the overall process for effort flow analysis.

Chapter 5 covers the conduct of an empirical study designed to extract and capture design knowledge in the form of a set of fundamental effort flow analysis guidelines. The guidelines that result from the study are integral to the overall directed product evolution methodology that is effort flow analysis. In fact, the product evolution guidelines complete the effort flow analysis methodology to the point where it can be presented comprehensively. Chapter 6 presents the complete theory of effort flow analysis along with a practitioner's version of the method in the form of a multi-step process. Each step of the practitioner's version is accompanied by insights about its implementation. Chapter 7 provides the proof of the method by taking the practitioner's version and applying it to a product. The result is a functional prototype of the evolved product that demonstrates not only the power of the method, but also the similarity between the outcome of effort flow analysis and other concept generation approaches.

Finally, Chapter 8 provides closure to this phase of the research effort in effort flow analysis. The perceived contributions of this work are highlighted and the resulting potential for future is explored.

Chapter 2 - Background and Related Work

2.1 - DESIGN PROCESS MODEL

The design process model presented in this chapter is a compilation of observations from the literature. In general, the goal of a design process is to synthesize alternative systems that perform a set of desired functions, meet the required performance standards, and satisfy the constraints. In doing so, the design progresses through varying levels of abstraction, from initially discovering what the customer wants and expects to the embodiment of the final design. At each level, the process is iterative and achieves incremental progress on a portion of the problem moving toward its ultimate solution.

The design process considered in this dissertation is presented in Figure 2.1. The overall design process is expressed as a hierarchical model that begins with the customer needs. The *customer needs* (CN's) represent the voice of the customer in the design process; they model the essence of the interaction between the design artifact and the customer. In this context, a customer may lie anywhere along the path from manufacturing to end-user.

Based on the CN's, the next step in the design process is to develop a *process description* for the design. Developing the process description involves analysis of the observed or projected use patterns over the product life cycle, as well as the process choices that facilitate those use patterns; e.g., choosing electric power over internal combustion engine power. The process description leads to a *black box model*, where specific inputs and outputs to the system are determined based on the process choices and use patterns previously stated. These inputs and outputs are the major physical flows of the system, and are classified as: energy, material, or signal [49].

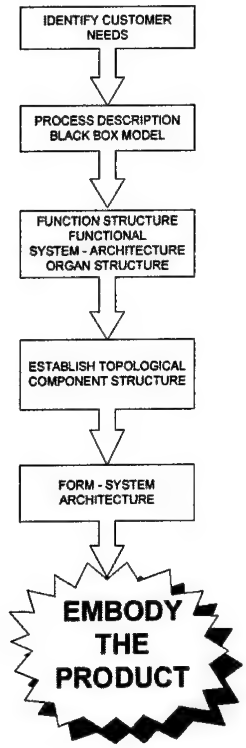


Figure 2.1: Design Process Model [50]

The next level of the model is the *functional model (or function structure)* [1, 49, 51-53], which is a form-independent expression of the product design. The functional model is a domain independent network of functions representing all the necessary working principles needed to carry out the transformation of the physical flows from input to output. These functions are selected from a set of standard functional elements known as basis functions [54]. Each basis function is a primitive element that satisfies the required input/output relationship at a particular node within the network, but is in general energy domain independent.

This network of functions spans the function space such that all input/output requirements are satisfied. The goal at this level is to refine the architecture of the network in search of a preferred functional solution for satisfaction of the CN's. This optimized (or preferred) arrangement is known as the *functional system-architecture.* At this level of abstraction, the system has a specific functional architecture that is capable

of carrying out the functional requirements of the design, but has no specific physical embodiment.

Further refinement of the design leads to the *organ structure,* [55], where heuristics are used to identify functional elements that can be gathered together to form functional modules [1, 56]. Global product architectural decisions may be made at this point, such as modularity vs. integral architectures. At this point, the design is fully described in terms of functions.

The next level of abstraction associates specific devices with the basis functions used in the function structure. This level represents the *topological component structure* of the design. Here, structural elements, or devices, are creatively generated or selected to satisfy the input/output requirements at each node in the network. Because these are "real" devices, their interface specifications constrain the system configuration leading to a component topology.

The final level of the model is the *form system-architecture.* This is the least abstract level in the process, where the design is now fully embodied. The goal at this level is to optimize the physical embodiment of the alternative designs that have emerged. It is at this level of the design process that design methods are applied to optimize the embodiment to satisfy the CN's in the most efficient and effective manner possible with the available resources.

The goal of presenting this design model is to set the framework within which effort flow analysis must function. Effort flow analysis is a synthesis technique that requires the existence of a rudimentary understanding of the components and their interfaces within the product. Hence, effort flow analysis becomes operational at the *topological component structure* level of abstraction, and continues through to *embodiment* of the design. Effort flow analysis is now established within the design model, now it is appropriate to discuss how this research effort fits into the overall scope of engineering design research.

2.2 - RESEARCH MODEL

The research model presented in this chapter is based on the observation that engineering design research is carried out in both academia and industry, but the driving

force behind engineering design research must originate, or at least be targeted, in industry [57]. Industry provides the motivation for revision and extension of existing tools and methods as well as the seeds for the germination of new ideas. Development of these tools and methods needs to be nurtured by both academia and industry, but validation must ultimately come from its use in a "live" product development environment. The mechanism for transmission of new and improved methods from research to industry has multiple paths. These paths exist both within industry alone, and between industry and academia by way of university/industry cooperation and by way of the classroom where current research results are incorporated into coursework. Each of the block elements of the research model represents an area of active research in engineering design.

A schematic of the research model is presented in Figure 2.2, where the parenthetical references in several of the elements: Criteria, Description I, Prescription, and Description II, are based on the work of Blessing, *et al,* [58]. These references provide a basis for common understanding in design research. The elements of the model are described in more detail in the following paragraphs.

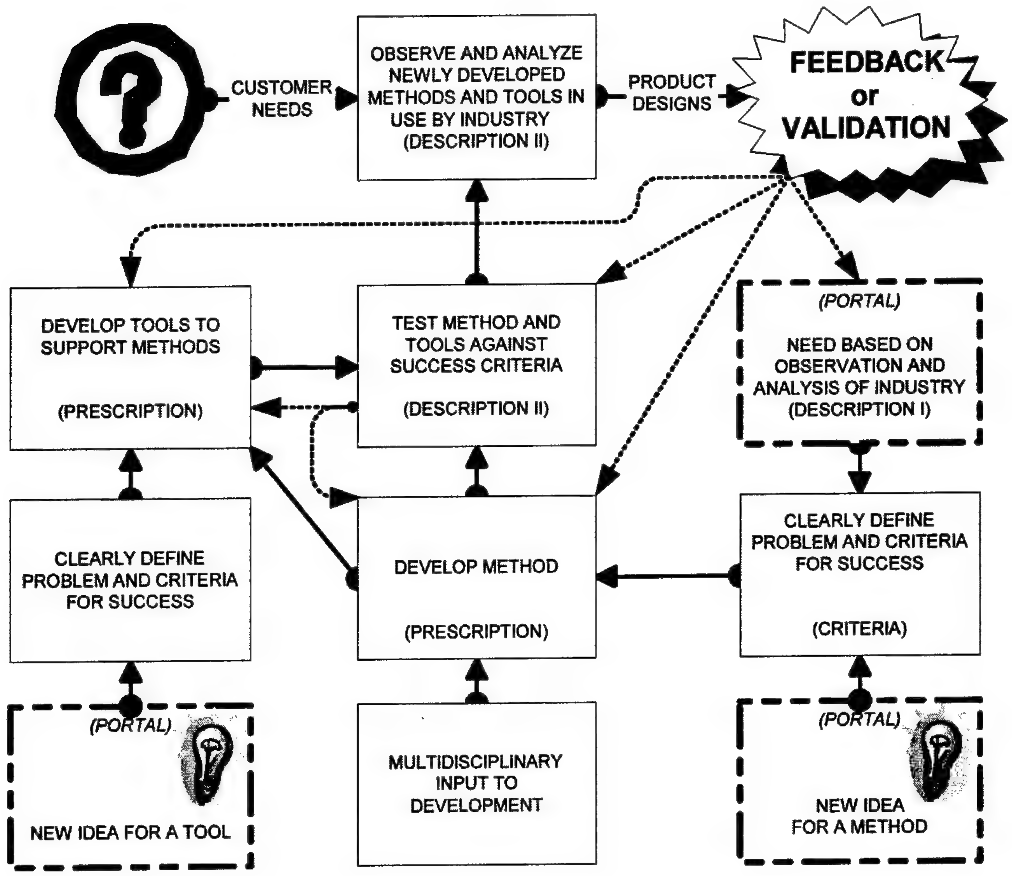


Figure 2.2: Design Research Model.

The blocks in Figure 2.2 with bold frames indicate portals of entry to the model. These entry portals represent opportunities for research contributions to the field of function-based design research. Clearly, there are two classes of opportunities, those originating from observation and analysis of industrial practices and processes, and those originating from perceived or expected needs based on original thought (the light bulb). The former are based on descriptive studies of the way product development is done in industry, and the latter are based on intuition, experience, and logical reasoning. In this context, the phrase descriptive study is meant as a study that is in the form of or based upon a coherent theory, not the more common meaning of being vivid or graphic in nature. Both approaches have merits, but it is proposed by Blessing *et al,* [58] that the

descriptive study approach provides the greatest opportunity for dissemination and acceptance of the resulting methods and tools.

Following the flow of an idea from an entry portal to the development element ("Develop Method" or "Develop Approach") indicates that for any concept to be developed into a method or tool, it must pass through the problem definition and criteria generation element. Problem definition is a critical element in the research model. Without clearly defining the problem to be studied, much effort will be expended in tangential directions without performing useful work in the needed direction. While this "exploratory" approach may be acceptable, or even encouraged, in a university laboratory setting, it is an undesirable approach to industrial research. According to Schregenberger [59], design methodologies are an integral part of the broad based management strategies used to increase the stakeholder value of an enterprise. In this environment, a directed action approach to design research is more appropriate, and hence the emphasis on clear definition of the problem and its objectives. The "criteria," as used in this element, are defined as the performance metrics by which the research will be evaluated. Blessing, *et al,* [58] identifies two types of criteria used to measure the success of a research project. The industry measure of success is the market impact of the method or tool that results from the research project, while the laboratory measure of success is satisfaction of the technical requirements used to define the research project at the outset. To be effective as measurement tools, the criteria must be objective measures and some difficulty may be encountered in determining relevant metrics for performance measurement [60].

The *method-development* element ("Develop Method") of the model is one of the two primary areas of research in design methodologies (tool development is the other). The prescriptive aspects of the engineering design research model are discussed here. This element is prescriptive in nature, i.e., prescribed by the innovation and thought processes of the researcher, because the outcome is in the form of instructions, heuristics, guidelines, theory, or advice for practice and application of a method. The essence of this element is the synthesis of useful mechanical design methods based on the results of descriptive studies. Note the inclusion of the multidisciplinary element, which feeds directly into development of the method. This aspect of method-development has been highlighted to bring attention to the need for involvement of disciplines other than

mechanical engineering in the method development process. The reasons for this comment are based, first of all, on the fact that method-development is, in and of itself, a design effort, where the artifact being designed is related to the creative process of synthesis, and must involve the sciences that are best suited for understanding such efforts. A second reason for involving experts from other disciplines is the fact that the resulting method must be integrated into a much larger enterprise of product development in the business domain. Pahl [61] highlights a chronology of collaborative efforts in engineering design research. Schregenberger [59] pleads the case for involving these other disciplines because they provide expertise in areas well outside the domain of engineering, areas such as business and industrial management, cognitive psychology, organizational psychology, and sociology to name a few. Several of these disciplines have expertise in clinical experiments using the scientific method, which is invaluable in researching the behavior and internal processes of designers who are engaged in synthesis. In order to make the developed methods more usable in engineering practice, there must be an interface between the method and the engineer, that interface is provided by the tools that are developed to support the methods.

Tool development is a prescriptive effort that leads to instructions, directions, worksheets, or procedures relating a design method to its practical application. Full-scale development of tools is typically a commercial venture carried out by software firms and consulting groups, but the seed that leads to commercial exploitation invariably comes from research. There are two possible paths leading to the tool development research element, the first is as an extension of method-development just discussed, the second path is independent of any current method-development research. As an extension of *method-development, tool-development* is a continuation of the process where applying the method to engineering practice is the primary consideration. The independent path approach is the result of perceived or expected needs and is based on original thought (the light bulb). This independent path approach is typically based on the recognition or supposition of the need for a new or improved tool that is associated with an existing design method. Once a method and/or tool have been developed, their suitability for use must be evaluated. As such, this path implicitly includes an element of peril, i.e., if the perceived need does not exist, the resulting method will likely not be accepted or used in

actual product development. This inherent danger calls for more industry data to validate research efforts, as shown in the model; however, the independent path approach is still needed to cause bifurcations and leaps in the practice of engineering design.

The methods and tools that result from design research must be tested and validated before they are promoted to industry for implementation. The bottom line is that as researchers, we must ensure that the criteria developed based on descriptive analysis of industry data are used to guide the research and thus lead to useful results. The next two elements of the model are associated with the Description II nomenclature proposed by Blessing *et al,* [58], and represent the testing and validation process for a method or tool. As the *description* moniker suggests, this is a descriptive study element. Blessing *et al,* highlight two principal difficulties with the validation of design methods and tools, they are: "(i) to identify whether the method or tool has the expected effect on the influencing factors that are addressed directly; and (ii) to identify whether this indeed contributes to success."

The *test-method-and-tools-against-success-criteria* element is designed to address the first of the issues highlighted by Blessing *et al,* In this element, the method or tool is tested and evaluated against the success criteria determined at the outset of the research project. A model/tool that successfully satisfies these criteria will proceed to the next level of validation, while an unsuccessful candidate will be evaluated to determine what further research and development is needed to satisfy the success criteria (iteration/feedback).

Ultimately, the goal of engineering design research is to develop methods and tools that contribute to the success of designers in industry. In order to understand the appropriateness and usefulness of the research, the methods and/or tools that result must be observed and evaluated in an industrial setting [58]. The *observe and analyze newly developed methods and tools in use by industry* element is designed to address this issue by validating the results of design research in an industrial setting, with the preferred setting being a "live" design project. The designs that result from this element are evaluated to determine the efficacy of the method or tool used to execute it.

A second level of feedback is initiated at this level. The resulting designs are analyzed, and the results are fed back to several levels of the design research model. This

feedback allows researchers to fine tune their efforts toward more effective methods and tools. In addition, a new round of descriptive studies is begun, thus allowing the studies to evolve to higher levels of refinement. The motivation for this entire effort comes from the fact that the customer of any engineering design research effort is the designer who uses the results, and our goal as researchers, and designers of design methods and tools, is to delight the customer [1]. These final two elements are critical to the ultimate success of integrating engineering design research into industry, as the research must satisfy some need and it must be usable in real-world design situations faced by design engineers.

2.2.1 - EFA and the Research Model

The purpose of presenting an overall research model is to provide a frame of reference for the work presented in this dissertation. The entry portal for effort flow analysis is mixed between the *new idea for a method*, and the *need based on observation and analysis of industry.* The idea for the new method sprang from observation of an industry need for a systematic approach to the identification of part-count reduction opportunities. Evolution to method followed observation of trends in the literature that led to a perceived need for a method leading to the synthesis of compliant mechanism solutions in product development. Effort flow analysis is currently in the transition between research and industry. The method is taught in the classroom at both the undergraduate and graduate level at the University of Texas at Austin, and at other institutions. As stated in the previous section, the ultimate goal of a design process is to synthesize alternative systems that perform the desired functions, meet the performance standards, and satisfy the constraints. The methods and tools that spring from engineering design research are the catalyst for design processes and the resulting synthesis. For product design, this synthesis process results in the incremental evolution of a product or design concept toward an ideal end. This is the essence of product evolution.

2.3 - Effort Flow Analysis to Date

This dissertation presents techniques to help accomplish the task of aiding designer in systematically identifying opportunities for piece count reduction. The layout

for this section is to review force flow analysis [1, 46, 52, 62], and then to show how force flow analysis can be used to identify creative opportunities for part combination in complex assemblies where relative motion exists between components.

2.3.1 - Prior Art

The seed for effort flow analysis comes from the concept of a force flow diagram first presented by Lefever [62]. Lefever *et al,* conceived of the force flow diagram based on intuition about an approach to identifying component combination opportunities in existing products. The force flow diagram is an embodiment of one of the component combination guidelines posed by Boothroyd and Dewhurst [6] in their seminal work on design for manufacturability and assembly (DFMA). The essence of the rule for component combination based on DFMA was presented in the section on DFMA. The abridged version is that if a component doesn't move, and there are no material or assembly conflicts, then it should be combined with its neighbors.

Hence, a force flow diagram, as it was originally conceived, is a tool for identifying components that satisfy the first of these three DFMA guidelines. Lefever took intuitive insights gained from the force flow diagrams and developed a rudimentary analysis technique, known as force flow analysis.

2.3.2 - Force Flow Analysis

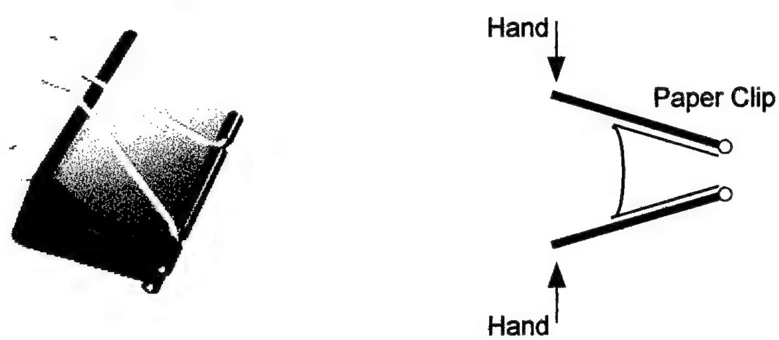
Force flow analysis focuses on identifying candidates for combination by virtue of the fact that a component does not move relative to interfacing components. Identification is accomplished through analysis of an abstract graphical representation of the actual design known as a force flow diagram. The force flow diagram is an abstract model of the product in the form of a semantic network. The force flow diagram models the product as a set of interconnected nodes and links.

Force flow diagrams use nodes, (circles), to symbolize the components of the product, and links (directed arrows) to represent the force transmitted through the interface between adjacent components. Using this network of nodes and links, the force flow diagram models the transfer of force from the point where the force crosses the system boundary as an input to the product, then tracks the force to the point where the

force again crosses the system boundary and is transmitted to the surrounding environment. Hence, the term "force flow" is intuitively appropriate for describing the transmission of forces through a product.

Use of the term "Force Flow" is not unique to Lefever's work; Chow [63] uses a force flow concept to visualize stress concentrations in components in a manner similar to the use of streamlines in fluid flow. Using Chow's approach, lines of force are shown to be more concentrated in areas where geometric discontinuities exist, hence highlighting the location of a stress concentration. Juvenal and Marshek [64] use the force flow concept to assist in visualizing the "flow" of forces through machine elements. Here, detailed sketches of the elements are annotated with lines representing the force path through the individual component. Both these applications concern themselves with the details of individual components and the stresses that exist within those components. Force flow is fundamentally similar, but is applied to the entire product as a system.

As a simple demonstration of a force flow diagram, consider the three-piece paper clip shown in the Figure 2.3(a) and Figure 2.3(b). Here, the hand transfers force to each lever arm, which in turn transfer the force to the clip. This flow of force is represented in the force flow diagram in Figure 2.4(a). No work piece is present in this example, so the force flow goes into the clip and stops there.



(a) (b)

Figure 2.3(a): Rendering of a Binder Clip; (b): Paper Clip Schematic

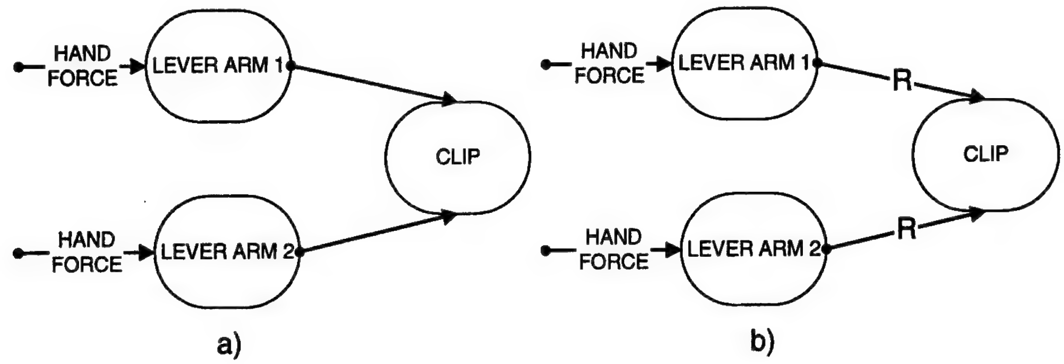


Figure 2.4: (a)Force Flow Diagram, & (b) Modified Force Flow Diagram for Binder Clip (original diagram format)

This simple example illustrates the original force flow diagram approach to mapping the force flow through a product. To apply the analysis step, the diagram is further modified as in Figure 2.4(b) by placing an "R" on the flows (links) where relative motion between two components occurs. Specifically, two interfacing parts will be considered to have relative motion between them if, during operation of the device, any point on one part has relative velocity with respect to any point on the other part. Once the diagram modification step is completed, the model can be decomposed into groups of parts separated by "R's." The model shown in Figure 2.4(b) doesn't have any "R-groups" because all the components move relative to one another during operation of the product. In general, having performed the separation of components into R-groups, the following proposition is made:

> Proposition: The components comprising "R" groups are candidates for combination if not prohibited by material or assembly/disassembly issues. Combination between a member of one group and a member outside of the group may be possible but requires more complex redesign. [62]

The prohibition against combining components outside the R-group in the original force flow analysis proposition is based on theories of mechanical systems design and machine element design. In a mechanical system, two parts that purposely move with respect to each other do so to provide a function(s). Therefore, eliminating a motion means eliminating a function, which is generally undesirable from the standpoint of satisfying customer needs. Combination of components outside an "R"-Group

requires a new functional representation resulting in a more involved adaptive redesign effort. On the other hand, components within "R" groups do not move relative to each other, hence combination of non-relative motion components is less likely to require functional redesign. Therefore, non-relative motion components can be combined unless combination is prohibited by material property or assembly/disassesemby issues. The material and assembly constraints on component combination are directly related to the component combination guideline criteria set forth by Boothroyd and Dewhurst and discussed earlier in this chapter. Force flow analysis is conceived as a systematic technique for identifying component combination opportunities that satisfy the criteria established by Boothroyd and Dewhurst.

It is important to note that force flow analysis has made the transition to industry discussed in the research model of Figure 2.2. The following example demonstrates an industrial application of force flow analysis, and is an excerpt from some previous works on force flow analysis [1, 22, 52, 62].

2.3.3 - Industrial Example Using the Force Flow Method

This example is included to illustrate the transition of effort flow analysis from a research environment to industrial implementation. Force flow analysis has been successfully used to reduce part count in a variety of industrial cases. This example from the automotive industry concerns a Slide Out Auxiliary Visor (SOAV) as shown below. The motivation behind an auxiliary visor is to provide a means of blocking light in front of the driver or passenger, while the traditional fold-down visor, in the swiveled position, shields light coming from the side. Most auxiliary visors consist of a second fold down visor contained above the headliner that must first translate out, then rotate down to block incoming light. A schematic of the product layout is shown Figure 2.5, which illustrates the SOAV in the translated position.

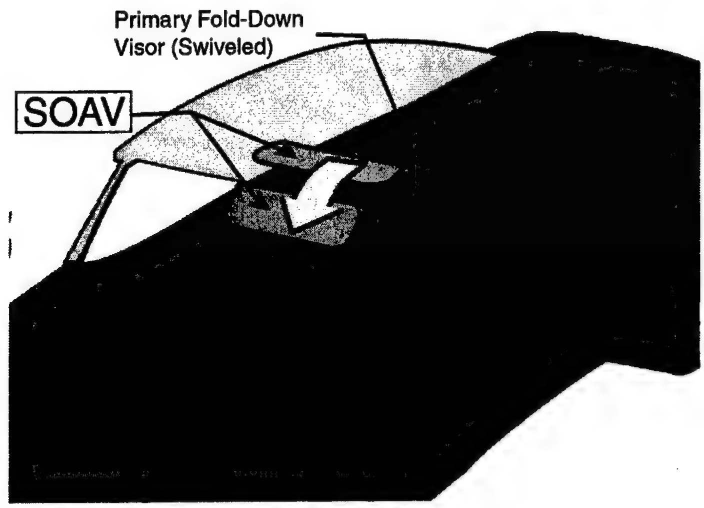


Figure 2.5: Simple schematic of SOAV operation

The SOAV assembly is a high volume product consisting of 40 parts (Figure 2.6). As a high volume product, reducing the assembly costs for each SOAV is an important issue. Reduced assembly time can be achieved through simplifying the handling and insertion of certain components or by reducing the number of assembly operations. Because 40 parts is considered a large quantity for the function performed, reducing the number of parts will likely lead to a greater reduction in assembly time than simplification of the assembly operations. This potential reduction in assembly time will likely reduce the assembly costs significantly indicating an opportunity to use force flow analysis.

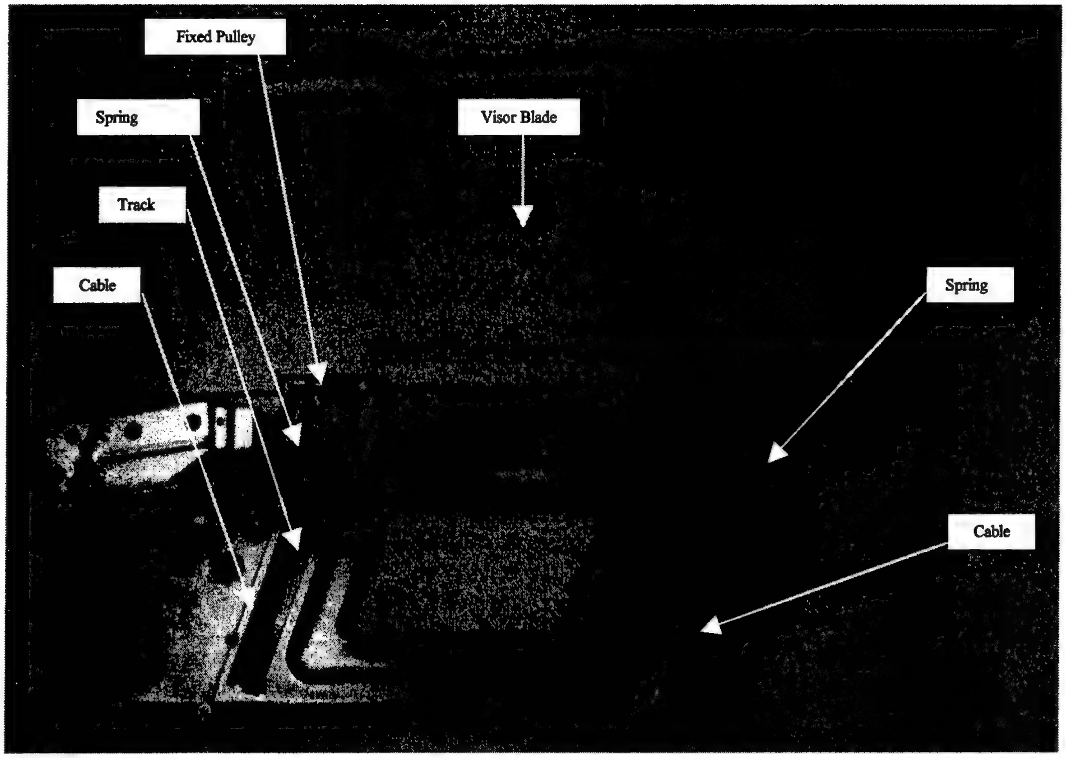


Figure 2.6: Annotated schematic of SOAV

Figure 2.7 shows the force flow diagram for the operation of translating the visor, then rotating it down. To analyze the diagram, an "R" is placed between components with relative movement. The components are then grouped between R-Links. Figure 2.7 displays two of the groups found in the force flow diagram. The adaptive redesign presented here will focus on the components contained in Group 2 from the diagram.

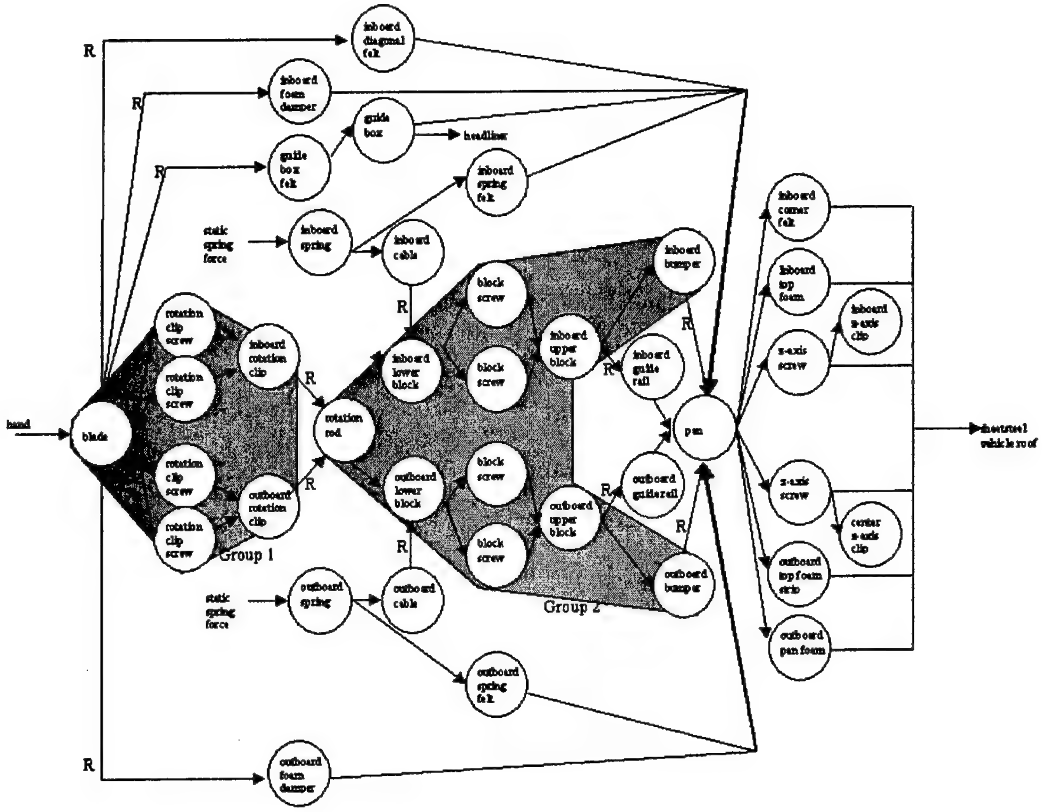


Figure 2.7: Force Flow Diagram for SOAV

The arrangement of the components in Group 2 is symmetrical. The rotation rod connects a series of inboard components and a series of outboard components, hence the redesign to one side can be duplicated on the other side, but combining components across the symmetry is more difficult.

Examining the force-flow diagram shows that the block screws that join the upper and lower slide blocks could are candidates for elimination using integral attachment. However, it would be preferable to simply combine the upper and lower slide blocks, but assembly/disassembly issues are involved. The adaptive redesign in Figure 2.8 shows how this assembly constraint is eliminated so the two components can be combined. The foam bumper between the upper and lower slide blocks is replaced with an o-ring. Assembly of the components is accomplished by rotating the block sub-assembly into engagement with the tracks, instead of constraining the assembly to a

vertical downward motion. Combination of the upper and lower slide blocks on the inboard and outboard sides leads to a reduction of six parts. This reduction can be verified in Figure 2.8 where the eleven original parts are shown in the top part of the figure and the five redesigned parts (2 O-rings, 2 sliders and the bar assembly) are shown in the lower part of the figure.

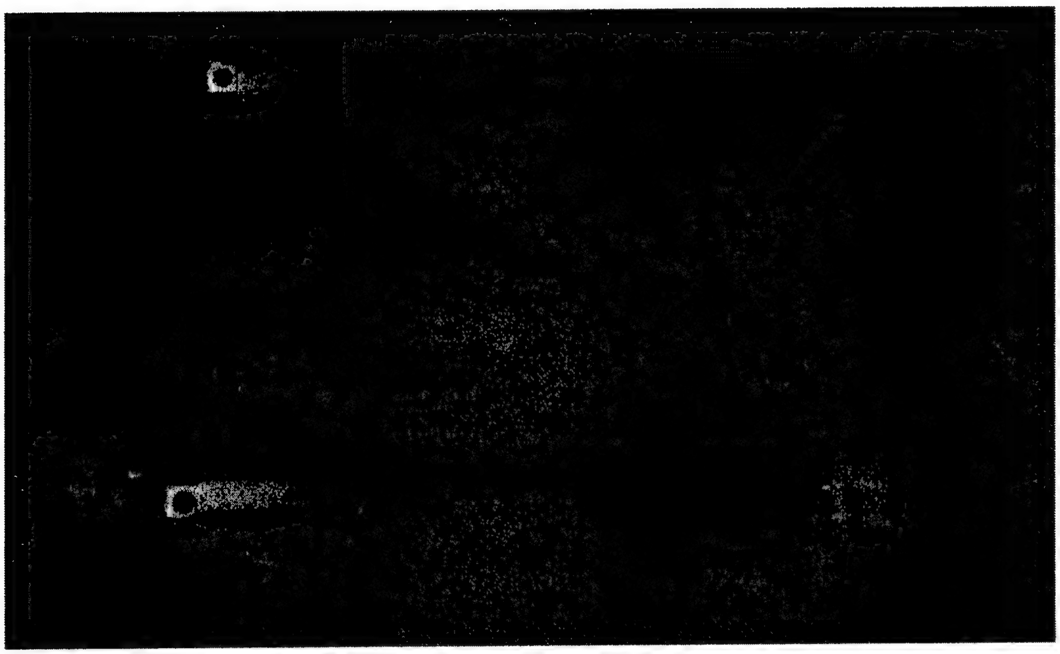


Figure 2.8: Original SOAV (Top) & New Single Slide Block Redesign (Bottom)

2.3.4 - The Redesigned SOAV

The task of reducing the piece count of the SOAV is accomplished using the force flow method as well as other techniques [52]. Using these techniques resulted in a redesign with a total of nine fewer components (six are directly attributable to force flow analysis) while maintaining the original functionality of the product. After implementation of the majority of these changes, the manufacturer realized lower manufacturing and vending costs and the implementation freed up assembly workers from the SOAV lines to work other assembly lines. Execution of force flow analysis to

this product alone translated into a *significant* annual savings for the manufacturer (millions of dollars)

2.4 - Related Work by Other Authors

Other authors have presented design methods that use modeling techniques similar or related to the force flow diagram. One such technique is presented by Steiner [65]. In this method, the connectivity of an assembly is quantified using a tool known as an interaction graph. Interaction graphs are semantic networks that represent the interactions between parts in an assembly. Steiner uses the number of connections and a ranking of the strength of those connections to determine the degree of integration or modularity of an assembly. The relationship between interaction graphs and force flow diagrams lies in the representation of interaction between members of an assembly. Force flow diagrams, as will be demonstrated, seek to identify the nature of connections between parts in order that appropriate parts can be identified for combination, while interaction graphs depict the number and strength of those connections to measure the degree of integration.

In a related method, forces between functional, or "work" surfaces lead to interaction-like graphs as part of a product model which can be used for product evaluation and redesign [66, 67]. This approach supports identification of functional overdesign but is more complex than the force flow analysis approach proposed by Lefever. In an approach that combines aspects of several other methods, Esponda [68] uses part connectivity and force flow to measure simplicity, clarity, and unity in a design and proposes a technique for manufacturability evaluation. Wallace and Stephenson build on this work to use force flows to predict and correct reliability problems [69, 70]. Finally, component relationship graphs are used for computer support of design synthesis and for assembly process planning, but these models capture more information than simply the nature of force flows [71, 72].

The work by Jacobs [73] is a CAD support tool for the management of complexity in design. The tool uses a representation of assemblies of parts into systems that is similar to that used in this dissertation, in that it characterizes the interfaces as an object having Assembly Features, Positioning Constraints, and a connecting Joint. The

Assembly Features are the compatibility features on each of the two interacting parts, these may be any functional, manufacturing, or form feature, or any geometric object. The Positioning Constraints are related to the shape of the components, and the Joint is the kinematic relationship between the components. Characterization of the kinematic relationship in the joint is the primary similarity between Jacobs work and force flow analysis, but the goal is quite different. The goal of the CAD tool is to react to designer inputs by notifying the designer when an assembly input would lead to increased complexity. Effort flow analysis, on the other hand, seeks to direct the designer toward the next design iteration, which will reduce complexity.

Chapter 3 - Theoretical Foundations of Effort Flow Analysis

The theoretical foundation of effort flow analysis will be discussed in this chapter. The foundation begins with the principles of classical mechanics, the study of statics, and the manifestation of statics in free body diagrams. A second component of the foundation is graph theory; the study of networks involving points, lines, and paths, that arose from the investigation of puzzles, properties of electrical circuits, and representations of connected structures. Mechanics establishes the fundamental principles of forces and motion, while graph theory establishes the fundamental concepts for developing a visual and mathematical representation of a system.

3.1 - MECHANICS

Any device that transfers a force from the point of application to another point where it is used is called a machine. The word machine has its origin in the Greek word for "invention "or "device," [74], machines that cannot be simplified further, such as levers, axles and wheels, and inclined planes, are called simple machines. Most mechanical devices in existence today can be constructed through the combination of two or more simple machines. Hence, the branch of physics that deals with the forces and motions of these simple machines is known as mechanics (classical). *Mechanics*, the science of forces and motion of bodies, is often used to denote the disciplines of *statics* when the body is motionless and *dynamics* when the body is in motion [75]. The word static comes from the Greek word meaning, "to cause to stand." The focus of this section is on the static realm of classical mechanics, as it forms a major portion of the foundation of effort flow analysis. As the Greek roots might imply, the earliest origins of mechanics come from antiquity.

3.1.1 - History

The earliest recorded works in the study of mechanics are attributed to the Greek philosopher Aristotle (384-322 BC). Aristotle wrote on many subjects amassing a collection of 150 volumes of lecture notes. His work in mechanics was observational in nature, and covered such topics as: the parallelogram of forces for the special case of the

rectangle (all forces orthogonal to one another), the theory of the lever, the resolution of the motion of a weight at the end of a lever into horizontal and tangential directions, and the laws governing falling bodies. Because of its observational nature, his work would not be considered rigorous by today's standards, nor were the results generally correct, but he significantly influenced those who would study mechanics for many centuries to come. Though Aristotle's approach was dynamic in nature, using the concept of virtual velocities, it had significant effect on the study of statics. Euclid (325-265BC) is credited with the first mathematical proof of the law of the lever in which a purely static state of equilibrium is used [76]; this credit is based on ancient Arabic translations of *Book on the Balance.*

Archimedes (287-212BC), a Greek mechanician, is the person cited as the originator of statics as an autonomous theoretical science [77]. Archimedes pioneered the theory of the center of gravity, and developed a proof similar to that of Euclid's for the theory of the lever. In Archimedes' *Equiponderance of the Planes,* he writes that equal weights acting at equal distances on opposite sides of a pivot are in equilibrium. He goes on to state "in the lever unequal weights are in equilibrium only when they are inversely proportional to the arm from which they are suspended." [76]

Hero, a Greek mathematician who lived about a century after Archimedes, continued work on the lever to include curved lever arms, and furthered the insight that the key characteristic of the lever problem is the horizontal distance from the fulcrum to the line of action of the weights. In addition, Hero's *Mechanics* stands as an initial, albeit incorrect, work on the problem of a weight resting on an inclined plane [76]. After the time of the Greeks, the fundamentals of mechanics were translated and incrementally advanced by the Arabs and the Romans [78].

The works of the Greeks lay virtually dormant during the Dark Ages until the twelfth and thirteenth centuries when European scholars began to translate the Greek and Arabic mechanics texts to Latin. These translations led to a rediscovery of the work of Aristotle by the learned classes of Europe and the ascendancy of Aristotle as the supreme authority in the realm of mechanics throughout the Middle Ages until the Renaissance (16^{th} century).

During the Renaissance, several scientists took up the study of statics, the most notable being Stevin (1548-1620). Stevin accurately solved the incline plane problem based on the impossibility of perpetual motion. He further extended work in the static analysis of systems of weights, pulleys, threads, and inclined planes leading him to become the originator of the use of graphical methods in the solution of statics problems [77]. Another contributor to the advancement of statics is Roberval (1602-1675). Roberval's first claim to fame in statics is that of having justified the law of the parallelogram of forces [77]. An illustration of the system used by Roberval to demonstrate his law of the parallelogram of forces is shown in Figure 3.2. Roberval considers weight **P** suspended at **B** by two strings **AB** and **BC**. The string passes through fixed point **A**. Roberval sets out to determine the force at **Q** applied to **BC** such that the **P** is supported in equilibrium. He replaces arm AB, whose length is fixed, by an *angular lever* **Ap, Aq,** where **Ap** is the perpendicular on the line of action of the weight **P,** and **Aq** is the perpendicular to the string **BC**. The equilibrium of an angular lever requires that:

$$\frac{P}{Q} = \frac{Aq}{Ap} \tag{3.1}$$

From this result, the value of **Q** is obtained.

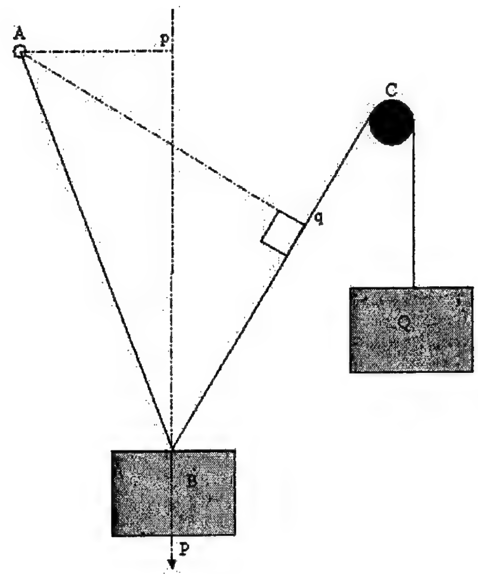


Figure 3.1: Roberval's Initial System (recreated from Dugas, [77])

The result from Figure 3.1 is then applied to the system in Figure 3.2. Here **QG** and **CB** are, respectively, perpendicular to **CA** and **QA**. Additionally, **CF** and **QD** are perpendicular to the line of action of the weight **A**. The weight **A** is suspended from the two strings, **CA** and **QA**, to which weights **K** and **E** are applied. The equilibrium of the lever **CF, CD** gives the ratio:

$$\frac{A}{E} = \frac{CB}{CF} \tag{3.2}$$

Similarly, the lever **QD, QG** gives the ratio:

$$\frac{A}{K} = \frac{QG}{QD} \tag{3.3}$$

The text of the law as reported by Dugas is as follows:

> "Therefore it is observed that in both cases two perpendiculars are drawn from each power – one on the direction of the weight and the other on the string of the other power. Also that, in the ratios of the weight to the powers, the weight is homologous to the perpendiculars falling on the strings of the powers. Similarly the powers are homologous to the perpendiculars falling on the direction of the weight." [77]

By these purely geometrical arguments, Roberval transforms the statement of the rule of the quadrilateral to the decomposition of the weight into its components in the directions of **CA** and **QA**.

> "If, from some point taken on the line of the direction of the weight, the line parallel to one of the strings is drawn to the other string, the side of the triangle thus formed will be homologous to the weight and the two powers." [77]

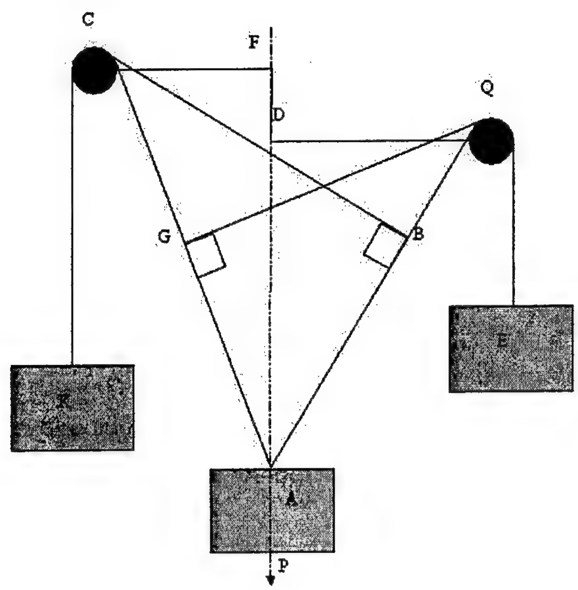


Figure 3.2: Roberval's Arrangement of Weights, Strings, and Pulleys (recreated from Dugas, [77])

Galileo (1564-1642) brought advances to the study of statics as well, but his greatest contributions were to the field of dynamics. Galileo expended considerable effort on the inclined plane in deducing his theory on acceleration. The inclined plane, in the form of a smooth sphere rolling in an inclined track, was used to model free fall. The inclined plane slowed the event to such an extent that his primitive time keeping device, a water clock, would have useful accuracy [74]. The resulting theory states that freely falling bodies will travel equal distances in equal times, regardless of their weight. In order for Galileo to use the inclined plane as a useful device, a solid understanding of forces and their components was necessary.

Galileo's work generated notable conclusions regarding the motion of falling bodies, projectile motion, and hydrostatics. The first two leading to an understanding of force and acceleration and the latter leading to use of the word "*momento*" to refer to the product of weight and velocity, the use of mass in momentum would have to wait for Huygens and Newton.

Galileo's writings demonstrate an early understanding of the principle of inertia where an object in motion or at rest will remain so, unless acted upon by a force, but he did not postulate a law of action and reaction [78] 1925). Galileo did formulate the principle of the *parallelogram of forces*, but did not fully recognize its significance [78]. Now, the groundwork is firmly laid for the development and use of a consolidated theory for the analysis of static and dynamic systems. It remains for one person to bring the disparate theories and results together.

Newton (1642-1727) was the one who brought together the ideas from those who had come before him to develop what we now know as classical mechanics. Newton did not simply consolidate the work of his predecessors and present them as a result; rather he assimilated the knowledge of the past and expanded it to encompass the universe as he saw it. His observations led to a set of deceptively simple "Laws" known as "Newton's Three Laws of Motion." These are: the law of inertia, the law of force and acceleration, and the law of action and reaction. The law of inertia; first stated by Galileo, and reformulated by Huygens is given by Newton as follows:

"*Law I. – Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.*" [77]

The law of force and acceleration, alluded to by Galileo is given by Newton as follows:

"*Law II. – The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.*" [77]

Finally, Newton gives the law of action and reaction as:

"*Law III. - To every action there is always opposed an equal reaction – or the mutual actions of the two bodies upon each other are always equal, and directed to the contrary parts.*" [77]

These three laws, are restated in the form of working definitions as they are used today:

"Law I. – A particle remains at rest or continues to move in a straight line with a constant velocity if there is no unbalanced force acting on it."

"Law II. – The acceleration of a particle is proportional to the resultant force acting on it and is in the direction of this force."

"Law III. – The forces of action and reaction between interacting bodies are equal in magnitude, opposite in direction, and collinear." [79]

Fundamental to the formulation of *Law II* is the fact that there is a distinction between the weight and mass of a body, such that the relation in Equation 3.4 is true.

$$\vec{F} = m\vec{a}\,. \tag{3.4}$$

The formal establishment of this distinction is another of the accomplishments attributed to Newton.

The impact of Newton's work is far reaching, as it brings the work of many of his predecessors to a consolidated set of laws that appear to work for the observable world, Einstein's theory of relativity not withstanding. At this point in the history of mechanics, the fundamental groundwork is laid for detailed analysis of machines and their components. Within the learned class, the following concepts are now established: equilibrium, forces and their vector components, the mass of an object, acceleration as a vector, interaction between bodies in contact, and force at a distance. An understanding of these concepts is fundamental to the development of analysis tools needed for the design and development of the complex machines in use today. One such tool is the venerable free-body diagram.

3.1.2 - Free-Body Diagrams

The free-body diagram represents a model of the system under scrutiny. To quote Meriam, [80] "the free body diagram is the most important single step in the solution of problems in mechanics." "This is so because the *isolation* of a body is the tool by which *cause* and *effect* are clearly separated and by which our attention to the literal application of the principle is accurately focused." The Free-Body Diagram (FBD) is a graphic representation of Newton's three laws. The First Law (equation 3.5) is represented for static cases, the Second Law (equation 3.6) is represented for dynamic

cases, and the law of action – reaction is represented in either case by the presence of forces acting upon the body of interest.

$$\sum \vec{F} = 0 \tag{3.5}$$

$$\sum \vec{F} = m\vec{a} \tag{3.6}$$

The FBD models an object as a "*body*" of interest isolated from its environment and details the interaction between the *environment* and the *body* through the forces acting *on* that *body*. The body can represent a particle, a collection of particles, a single rigid body or a system of rigid bodies. The terms *body* and *system* will be used interchangeably to refer to the body of interest throughout this manuscript. A properly constructed free-body diagram has the following components: a body, an axis system, reaction forces, applied forces, and dimensions. An example FBD taken from Roberval's system, previously shown in Figure 3.2, is shown here in Figure 3.3.

3.1.2.1 - Free-Body Diagram Nomenclature

The focus of the FBD is, as the name implies, the *body* of interest. A free-body diagram is created by first selecting the body of interest and defining a system boundary. In the mechanical design domain, the body of interest generally represents a single component or collection of components being investigated. It is generally chosen such that some desired unknown force acts on the body. In order to concentrate on only the cause and effect responses of the body, it is isolated from all adjacent bodies with which it interacts and from the surrounding environment. The isolation is carried out by defining a system boundary, a clear decision about the system boundary leads to a clearer understanding of the problem. Once isolated, a drawing of everything within the system boundary is created.

The drawing must include an axis system representing a useful reference frame. The reference frame should be convenient such that it lends itself to solution of the problem at hand. Several possibilities exist for the type of reference frame used, these include a body fixed frame, a local inertial frame, an Earth centered inertial frame, or an absolute inertial frame. These lead to very different formulations of a mechanics problem. For example, the fixed and moving frames lead to Eulerian and Lagrangian

formulations respectively. Newton's first two laws are known to be true in an absolute inertial frame, but require some correction for accelerating frames. This difficulty can be overcome for *most* engineering problems by choosing a fixed reference frame whose absolute motion is negligible for the problem at hand [79]. An axis system fixed in the Earth is a good example of this simplification.

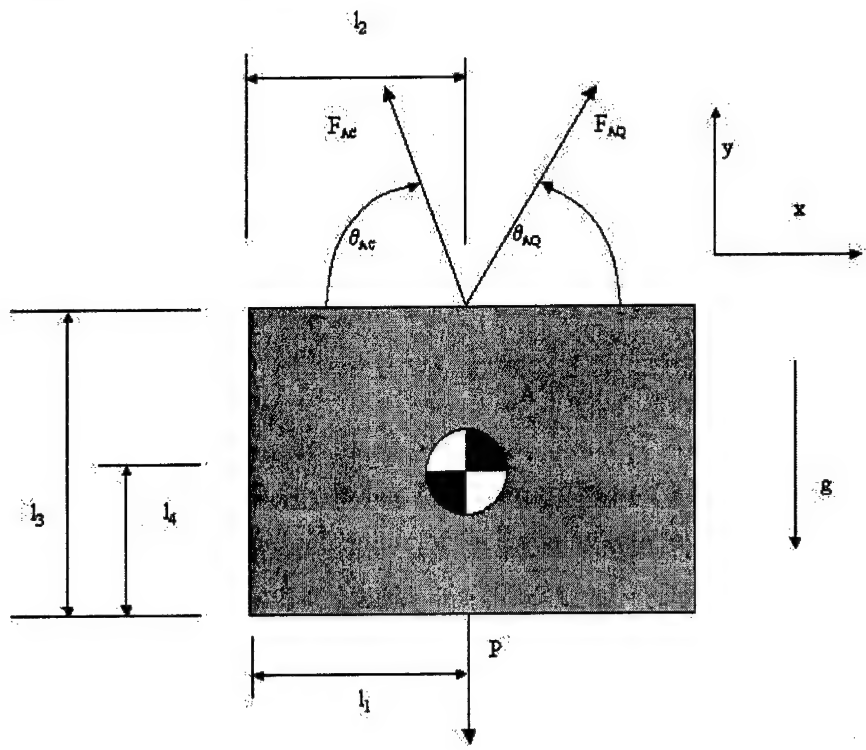


Figure 3.3: Example FBD from Roberval's System in Figure 3.2

Once the system boundary is defined and the body is drawn, all the forces crossing the system boundary are accounted for and depicted in the picture. The surroundings of the now isolated body are replaced by the vector forces of interaction, these forces may be due to direct contact with adjacent bodies or they may be forces acting at a distance due to field effects. The only forces represented on the FBD are the forces that cross the system boundary from outside; hence, internal forces are not represented. The forces shown on the FBD are represented in their proper location and direction on the body. The location of a force is dictated by the geometry of the body in

conjunction with the location and nature its interfaces with other bodies. The direction of the interaction forces is indicated using arrowheads on the force vectors, and both forces from the action–reaction pair are not depicted on the same free-body diagram.

An example free-body diagram is presented in Figure 3.3. In this example, the free-body diagram demonstrates the technique of isolating body **A** from the original system of bodies, and shows the forces, points of application, direction, and dimensions needed to solve for the unknown forces. A convenient reference frame is used to correspond to the inertial gravitational frame of the Earth. The unknowns in this case are the tension forces in the strings **AQ** and **AC**. Because the system is presented in static equilibrium, Newton's First Law is invoked to solve for the unknown forces:

$$\sum \vec{F} = 0 \tag{3.7}$$

$$\sum \vec{F}_x = F_{AQ}\cos\theta_{AQ} - F_{AC}\cos\theta_{AC} = 0 \tag{3.8}$$

$$\sum \vec{F}_y = F_{AQ}\sin\theta_{AQ} + F_{AC}\sin\theta_{AC} - P = 0 \tag{3.9}$$

In order to solve for the unknown forces, F_{AQ} and F_{AC}, and the angles, θ_{AQ} and θ_{AC}, the weight of the body, P, must be known. This represents the essence of the application of Newton's laws with the aid of the FBD as a graphical tool for collecting and displaying essential information.

The free-body diagram is rich with information about the geometry of the body and the nature of the interaction between the *body* and the environment around it. As illustrated above, free-body diagrams are an application of first principles in the field of mechanics, and can be applied to both static and dynamic analysis. In the case of static analysis, the free-body diagram depicts the body of interest in a state of static equilibrium.

3.1.2.2 - Static Equilibrium

The word equilibrium comes from the Latin words meaning, "equal weights." Static Equilibrium can be treated as a statement of Newton's First Law where all particles of a system move with uniform motion, or as a statement of Newton's Second Law where the sum of the forces impressed on a body equal to zero, leaving the overall system

unchanged. The condition for static equilibrium was stated mathematically in Equation 5. Applying *static* analysis to a system means that the forces and moments that are necessary and sufficient to satisfy the mathematical relationships implied by the First or Second Laws must be found. To maintain a system in a state of static equilibrium, the net force and net torque on the system must be zero. The tool used to determine the relationship between those forces and moments is the free-body diagram. Unfortunately, not all systems can satisfy this set of conditions. In cases where static equilibrium cannot be maintained, certain idealizations must be made.

3.1.2.3 - Quasi-Equilibrium or Kinetostatics

The principles of static analysis can often be applied when the equilibrium condition is not strictly satisfied, this type of analysis is known as *quasi- equilibrium* analysis. Quasi-equilibrium is an idealization of a dynamic system in which state changes are assumed to proceed from one state of equilibrium to another over very short periods [81], thus allowing the use of static analysis techniques. The conditions under which quasi-equilibrium analysis can be carried out are limited mainly to cases where the system is subjected to either slowly changing velocity reducing to a case where the first derivative of the system energy is near zero. One such area where quasi-static analysis is useful is the analysis of machine elements. There are, however, dynamic systems where static analysis can be used when the system is subjected to time varying accelerations. The technique used to carry out such analysis is known as d'Alembert's Principle [82].

3.1.2.4 - d'Alembert's Principle

d'Alembert's Principle was developed by Jean d'Alembert (1717-1783), and uses static equilibrium techniques to represent dynamic systems. d'Alembert's Principle as stated in Erdman, Sandor, & Kota, [83]: "The sum of the inertial or body forces and torques and the external forces and torques together produce equilibrium." In this approach to "static" analysis, the accelerations, either known or unknown, multiplied by the mass of the body or system are treated as constituents of the static force balance. Figure 3.4 presents an example system that includes the d'Alambert force. The Figure shows a particle **A** is subjected to two known forces, **P** and $\mathbf{F}_A$ resulting in an inertial

force, $\mathbf{F}_{ma}$. Analysis of the system is carried out in the same manner as if the body were in static equilibrium.

$$\sum \vec{F} = 0 \tag{3.10}$$

$$\sum \vec{F}_x = F_{ma} \cos\theta + F_A = 0 \tag{3.11}$$

$$\sum \vec{F}_y = -F_{ma} \sin\theta - P = 0 \tag{3.12}$$

The difficulty in applying the d'Alambert principle to this case is the addition of an unknown to the system, $\mathbf{F}_{ma}$ resulting in the need for an additional bit of information such as the value for $\mathbf{F}_A$ to solve the problem.

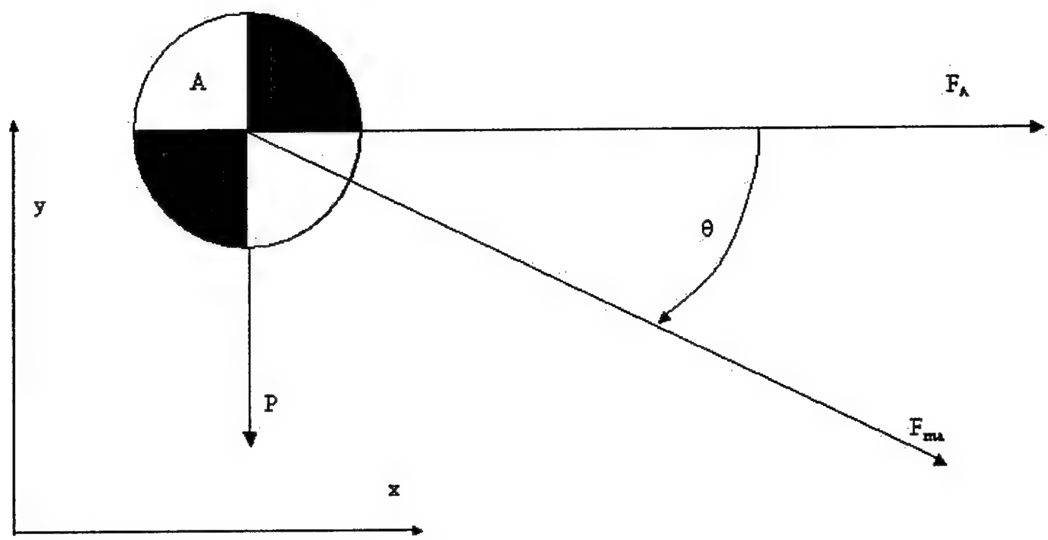


Figure 3.4: FBD Example Including the d'Alambert Force F_{ma}

Greenwood [82], finds extensive application for d'Alembert's approach to dynamic analysis, while Meriam and Kraige [79] relegate it to the role of historical reference as an approach from an era when static analysis was well understood and dynamic analysis was not.

Whether the analysis is static or dynamic, equilibrium or quasi-equilibrium, each of the approaches to the analysis of mechanical systems discussed here relates in a fundamental way to effort flow analysis.

3.1.3 - Conceptual Relationship between Mechanics and Effort Flow Analysis

On the conceptual level, mechanics forms the theoretical foundation needed to characterize the interactions between components in a system modeled using effort flow analysis. Products can be thought of as a system of components joined in a manner such that they perform intended functions. During the design phase, each of the components or subassemblies must be isolated and analyzed using techniques from several fields. For the field of mechanics, either static or dynamic analysis techniques are used; these will naturally include the use of free-body diagrams. Whether static or dynamic, the analysis requires that the interactions between each of the components or subassemblies be accounted for. If, after each component is analyzed in isolation, the system is assembled as a collection of free-body diagrams, then this system forms a network of interconnected bodies with the forces of interactions between each body shown as links between the interacting bodies. It is proposed that the resulting collection of free-body diagrams represents the foundational form of the effort flow diagram.

The effort flow diagram just described is the visual modeling tool of effort flow analysis. The primary benefit of the effort flow diagram is its ability to abstractly model component connectivity within the product. The effort flow analysis technique uses information about component interaction to highlight opportunities for directed evolution of the product. In order to make these opportunities more obvious, it is desirable to model the product in an abstract way. Abstraction is important in the modeling of effort flow analysis as it allows the product to be modeled without explicit knowledge of the system form. In order to capitalize on the advantages of using abstract modeling, the representation chosen for effort flow analysis removes many of the details related to the exact geometry of the product. In this simplified format, the product is represented as a connected network, or graph, consisting of links and nodes known as an effort flow diagram.

The requirements for modeling a body or system of bodies using the free-body diagram were discussed in detail earlier in this chapter. These requirements are relatively straightforward and will be used to show the correspondence of the FBD to the effort flow diagram.

3.1.3.1 - The Body

To begin, a clear decision is made about the body to be modeled. In the context of product modeling, this decision reduces to whether the model will be a single component or a collection of components. The result of this decision determines the system boundary for the model. If the modeling goal is to understand the overall product, then the choice must be made to model a collection of components. A further decision is required regarding the level of understanding desired. To understand the interaction of the product as a whole with the external environment will require that the collection be modeled as a single rigid body, but to understand the product beyond this "black box" level requires a model of the product as a system of interacting rigid bodies. Each of these rigid bodies is a lumped parameter model of the actual system and requires an amount of information to describe it; where the amount of information depends on the level of the analysis. For example, the information requirement for detailed stress and deformation analysis is greater than the information requirement for static analysis. Hence, the level of analysis dictates the level of information required for describing the body.

It is proposed in this dissertation that the key indicator for component combination is essentially the presence or absence of relative motion between components. Effort flow analysis, using the effort flow diagram as a tool, is an analysis technique for the identifying component combination opportunities based in part on relative motion. Hence, the level of information needed to describe a body in effort flow analysis is limited to that which allows the detection of relative motion between an individual component and the components with which it interacts. The representation from mechanics that has the appropriate level of information content to model the individual components of a product is the particle. In mechanics, the particle is idealized to have no mass or physical dimensions, and can be graphically represented as a single node. This abstraction of a component allows the amount of information required to describe the body be minimized to an appropriate level in effort flow analysis. The resulting amount of information needed to model the product in effort flow analysis is then greater than that of a "black box" model but less than that needed for static analysis.

3.1.3.2 - The Forces

Once the body of interest is determined for the free-body diagram, the forces of interaction must be identified and represented with their proper magnitude, direction, and sense indicated. The forces of interaction are generally regarded as the contact forces and the field forces that affect the body of interest by crossing the system boundary. In addition to the vector nature of the interaction forces, further information about the location and means of application of the forces may also be required. The location of force application deals with the geometry of the body and the exact location of force application on the body. When detailing the means of force application, the distinction between point loads and distributed loads must be made. As was the case when deciding on the level of detail needed to describe the body, decisions about the information content needed to describe the forces depend on the level of analysis being done. The more detailed the analysis, the greater the information requirement.

In effort flow analysis, the goal is to detect relative motion, which requires an understanding of the behavior of bodies in the interface region. An interface is defined to be "A spatial region where energy and/or material flow between components" [8]. Using this definition in the context of effort flow analysis, it follows that the contact forces coupled with the motions of interacting components indicate the flow of energy. Therefore, the contact interaction forces define the interfaces between bodies in the mechanical domain. It then becomes apparent that the interfaces, and associated contact forces, are a critical aspect in identifying relative motion leading to the identification of product evolution opportunities. Hence, effort flow analysis uses the interfaces between components as the logical way to represent the forces of interaction and to classify the relative motion between components.

In order to use effort flow diagrams as a catalyst for product evolution, the information needed must at least include the contact forces and the nature of the relative motion at the interface. Beyond this minimum requirement, other information may be included when necessary. The representation of interfaces in the effort flow diagram is greatly simplified from what is represented in the FBD. Effort flow diagrams depict interfaces as directed arrows, these arrows show the interface between components by virtue of the connectivity of the end points of the arrow, and indicated the direction of

forces using the arrowhead. Relative motion information is captured in the link labels associated with each interface. A separate link is created for each unique component interface. This is consistent with normal practice in FBD construction where separate forces are drawn for each point of contact on a body, even when multiple points of contact result from the same object.

Since relative motion is the key indicator of opportunity in effort flow analysis, it is not necessary to display other information such as the magnitude and direction of forces on the diagram. In addition, because of the decisions made regarding the use of a particle representation for the body, information about the location of force application would not be useful in the effort flow diagram, and need not be maintained. Again, the amount of information gathered and maintained will depend on the level of analysis being conducted.

3.1.3.3 - The Reference Frame

The final step in constructing a free-body diagram is to define a reference frame in which the problem will be solved. The reference frame can be local or global. The choice depends on several factors such as the availability of an inertial frame and the difficulty of transforming local frames to global frames. In the context of effort flow analysis, each component in the system will have its own local frame of reference. When needed, those local frames of reference can be converted to the global or product reference frame using appropriate transformations.

3.1.3.4 - Putting It All Together

Effort flow analysis is a systems approach to directed product evolution. A detailed view of an individual component provides little insight into the interaction of that component with the system as a whole. Hence, the view of the product represented in the effort flow diagram must include multiple components to be an effective tool in directing product evolution through component combination and/or removal. The goal is then to model the product in an abstract representation that contains all the information necessary to make an informed decision about what areas of the product are ripe for further attention and modeling, and which areas of the product should be left alone. To

create this abstraction of the product, each of the bodies from the individual free-body diagrams are shown in the effort flow diagram as simple nodes having no specific geometry. The forces of interaction are also simplified to the point that the magnitude and much of the direction information of the forces is neglected, only the sense of direction associated with the action – reaction law is maintained along with the connectivity of the interfaces.

The overarching rationale for the simplifications is the need for abstraction in engineering design. The use of abstraction fosters the discovery of a higher level of interrelationship within the system leading to the synthesis of new structures and creative new designs. In essence, abstraction supports both creativity and systematic thinking [49]. A further benefit of the simplification is that removal of the geometry and magnitude simplifies the representation of the product to only the interactions that are essential to determining preliminary opportunities for component combination. This is a conscious decision to forego detail at the initial design stage in favor of a clearer understanding of the overall interaction between components within the system. The abstraction process is aided by the representation of the components and interfaces in the form of a network. That network representation is based on the principles from the field of mathematics known as graph theory.

3.2 - Graph Theory

3.2.1 - History

According to Harary [84], Leonhard Euler (1707-1782) became the father of graph theory as well as the general field of topology when he published a paper in response to what is known as the Königsberg bridge problem [85]. The Königsberg bridge problem concerns an area that contains two islands linked to each other and to the banks of the Pregel River by seven bridges, as shown in Figure 3.5.

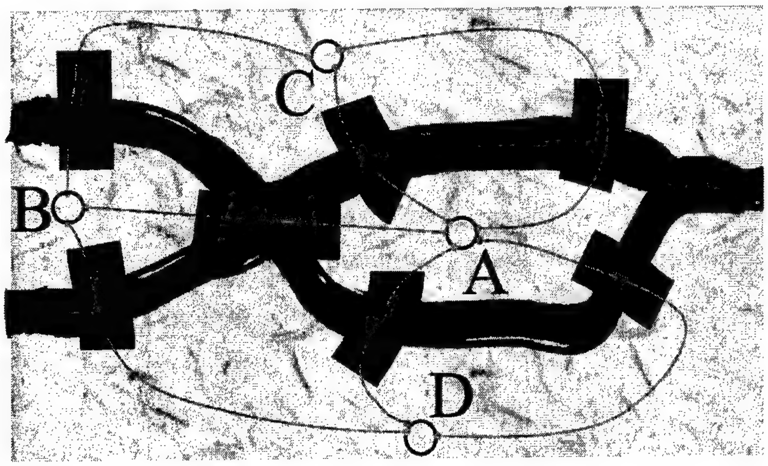


Figure 3.5: Königsberg Bridge Problem

The problem is to begin at any of the four land areas and, without swimming, flying, or traveling around the world, cross each bridge exactly once and return to the starting point. Euler used a connected graph, Figure 3.6, to prove that the problem had no solution. To do this, he constructed a graph with four nodes (A, B, C, and D) representing the land areas, and seven lines representing the bridges. Euler proved that there could only be a solution if every island had an even number of bridges touching it based on the logic that one must leave an island the same number of times one arrives at it. Alternatively, exactly two islands can have an odd number of bridges, and these must be the start and finish point of the tour. Euler generalized this mode of thinking by making the following definitions and proving a theorem:

Definition: A network is a Figure made up of points (vertices) connected by non-intersecting curves (arcs).

Definition: A vertex is called odd if it has an odd number of arcs leading to it, otherwise it is called even.

Definition: An Euler path is a continuous path that passes through every arc once and only once.

Theorem: If a network has more than two odd vertices, it does not have an Euler path.

Euler also proved the converse:

Theorem: If a network has two or less odd vertices, it has at least one Euler path. [84]

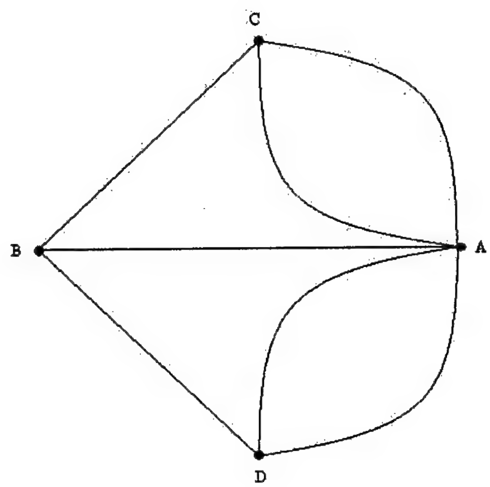


Figure 3.6: Graph of Königsberg Bridge Problem

From this humble beginning, graph theory has evolved to form its own branch of mathematics with applications in many fields of study. Two fields of particular interest to this work are the field of mechanics known as kinematics, and the area of engineering design concerned with product topology. The usefulness of graph theory in effort flow analysis is that is has an established nomenclature for graph construction and labeling. In addition, graph theory provides a tool for the analysis of the similarities between graphs that are visually dissimilar. To establish the graph theory nomenclature as a foundation for effort flow diagrams, some definitions are needed.

3.2.2 - Definitions

Formally speaking, a *graph* consists of a set of edges (arcs) and a set of vertices (points). The set of vertices are connected by the set of edges. The graph is denoted as ***G***, the vertex set as ***V***, and the edge set as ***E***. Each edge, ***e***, of a graph is connected on each end to a vertex, ***v***. An overall graph is specified as a **(*v*,*e*)** graph, for example, a graph with five vertices and four edges would be abbreviated as **(5,4)**. Edges are

specified as e_{ij}, where i and j denote the vertices at either end of the edge, these ends are the *end points* of the edge.

An edge is *incident* with a vertex when the vertex is an end point for that edge. Edges are *adjacent* when they are incident on the same vertex. The two end-point vertices of a single edge are also defined to be *adjacent*.

3.2.2.1 - Degree of a Vertex

The *degree* of a vertex is given by the number of edges that are incident with the vertex. The degree is *odd* or *even* according to the number of incident edges. For example, the degree of vertex **1** in Figure 3.7 is three.

3.2.2.2 - Order of a Graph

The order of a graph is the number of vertices in the graph. The graph representing the Königsberg bridge problem is fourth order.

3.2.2.3 - Walks and Circuits

A *walk* in a graph is a sequence of alternating edges and vertices, beginning and ending with a vertex. A *trail* is a walk in which all the edges are distinct. A *path* is a walk in which all the vertices (and thus all edges) are distinct. The *length* of a walk is the number of edges that occur in the walk. A walk in which only the beginning and ending vertices are not distinct is called a *circuit;* see Figure 3.7. A walk that contains all vertices of $\boldsymbol{G}$ is a *spanning walk.*

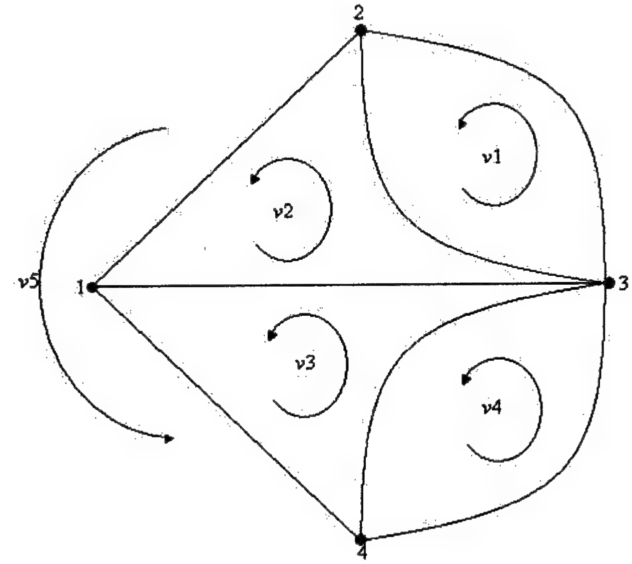


Figure 3.7: Graph Circuits for the Königsberg Bridge Problem

3.2.2.4 - Connected Graphs, Subgraphs, and Components

Two vertices are *connected* if a path exists from one vertex to the other. A graph ***G*** is a *connected graph* if every vertex in ***G*** is connected to every other vertex in ***G*** by at least one path, see Figure 3.8a.

A subgraph of ***G*** is a graph $\boldsymbol{G_{sub}}$ containing a subset of V and E from ***G***. This means that edges and or vertices are removed from ***G*** to form a new graph. The removal of a vertex implies the removal of the adjacent edges, but the removal of an edge does not imply the removal of vertices. For example, the graph in Figure 3.8c is a subgraph of the (7,4) graph of Figure 3.8a.

A graph ***G*** may contain several pieces called *components*. The components are themselves connected subgraphs of ***G***. Therefore by definition a connected graph has only one component, otherwise it would be a disconnected graph made up of components, see Figure 3.8c.

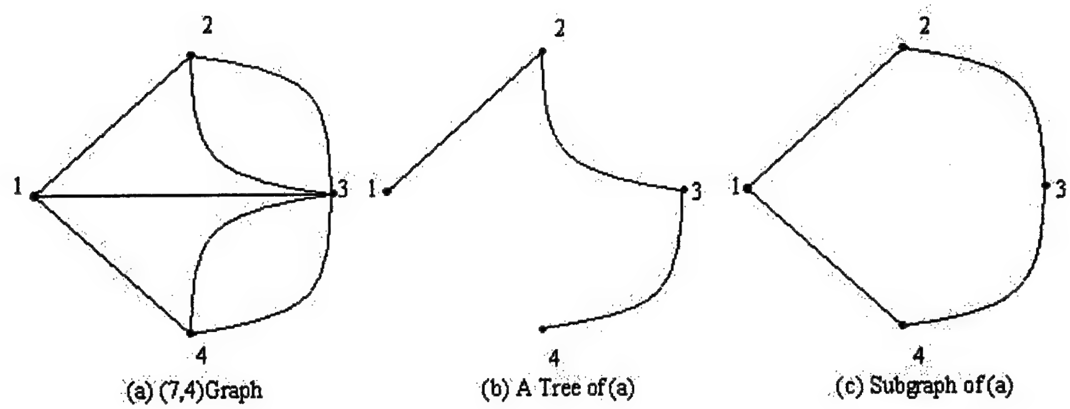


Figure 3.8: Connected Graph, Tree, and Subgraph Using Königsberg Bridge Problem

3.2.2.5 - Articulation Points, Bridges, and Blocks

A vertex whose removal results in an increase in the number or components is an *articulation point*. Similarly, an edge whose removal results in an increase in the number or components is a *bridge*. A graph that is connected and has no articulation points is called a *block*. The importance of these structures will become apparent when component combination is considered.

3.2.2.6 - Parallel Edges, Multigraphs, and Self-Loops

If the end-points of two edges are identical, then the two edges are said to be *parallel*. A graph that contains parallel edges is a *multigraph*. A *self-loop* is an edge that connects a vertex to itself. These graph structures are common in effort flow diagrams where compliant components are "self interfacing."

3.2.2.7 - Directed Graph and Rooted Graph

A *directed graph* has a direction assigned to every edge. A *rooted graph* is a graph where one vertex is uniquely identified as the *root vertex*. In a graph representing a mechanism, a root vertex is used to denote a fixed link or base generally associated with a support or ground reaction; see Figure 3.9. These tow concepts are of fundamental importance in the representing effort flow in a product model.

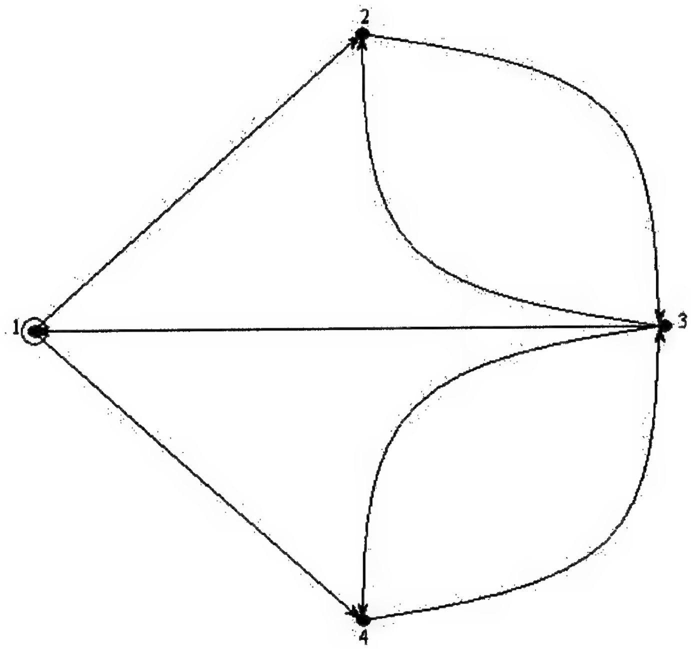
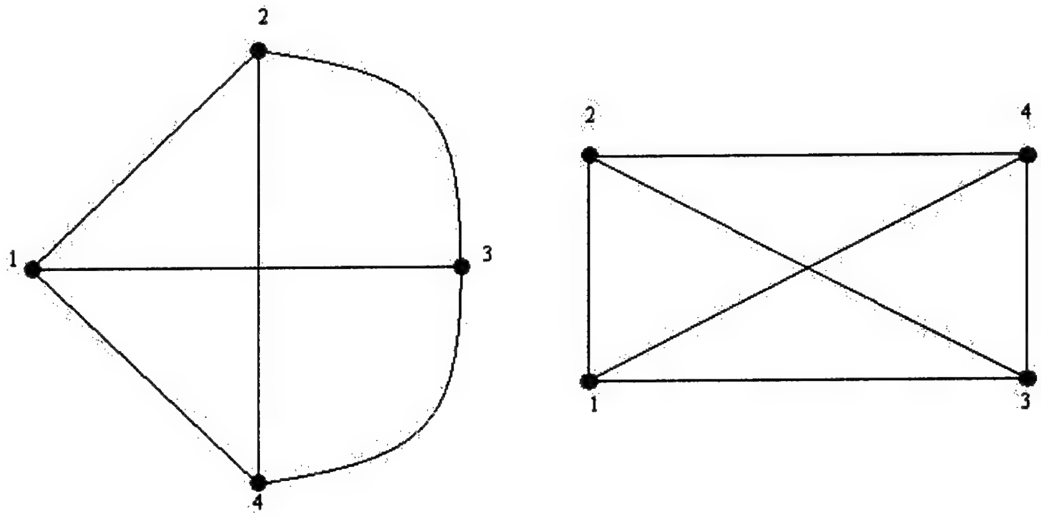


Figure 3.9: Directed Graph with a Root Vertex (Vertex 1).

3.2.2.8 - Complete Graph and Bipartite

A special case of a connected graph is the *complete graph* $\boldsymbol{K_p}$ *of order* $\boldsymbol{p}$ where every pair of vertices is adjacent. By definition, a complete graph has only one component. The graph shown in Figure 3.10 is an example of a $\boldsymbol{K_4}$ graph.

A graph $\boldsymbol{G}$ is said to be a bipartite if its vertices can be partitioned into two subsets, $\boldsymbol{V_1}$ and $\boldsymbol{V_2}$, such that every edge of $\boldsymbol{G}$ connects a vertex in $\boldsymbol{V_1}$ to a vertex in $\boldsymbol{V_2}$. A complete bipartite occurs when every vertex of $\boldsymbol{V_1}$ is connected to every vertex of $\boldsymbol{V_2}$ by one edge.



(a) Complete graph

(b) Isomorphic graph of (a)

Figure 3.10: Complete and Isomorphic Graph Examples.

3.2.2.9 - Graph Isomorphism

Two graphs, G_1, and G_2 are isomorphic if a one-to-one correspondence between their vertices exists that preserves adjacency. Two isomorphic graphs must therefore have the same number of edges and vertices, and the degrees of the corresponding vertices in each graph must be equal [86]. The two graphs in Figure 3.10 are isomorphic to one another. Graph isomorphism is a useful concept when comparing the graphs of multiple networks.

3.2.3 - Planar Graphs

A graph is *planar* if it can be drawn on a plane surface such that all edges are drawn as straight lines and no two edges intersect each other except at a vertex. The graphs shown in Figure 3.10 are not planar graphs, as they cannot be drawn a manner such that the edges will not cross. The graph in Figure 3.8c, on the other hand, is a planar graph.

well as any path within the graph. Each column of the matrix corresponds to a vertex (except the root) and each row corresponds to an arc of the tree.

The usefulness of the matrix representations for connected graphs will be shown when they are applied to effort flow analysis. This is especially evident when effort flow diagrams are implemented and stored on a computer.

3.2.5.3 - Contracted Graphs

A *binary string* of length k is a string of k vertices of degree 2 connected in series by $k+1$ edges. The first and last edges of a binary string are necessarily incident to non-binary vertices. A *contracted graph* is constructed by replacing every binary string in a graph by a single edge. The resulting graph will have no binary vertices, but may have parallel edges. This process of removing binary strings is called *contraction* of the graph. The combination of certain components in a product can be modeled as the contraction of a graph.

Given a conventional graph, the contracted graph is unique, but the addition of binary strings to a contracted graph can lead to an infinite number of conventional graphs. The process of replacing edges by adding binary strings is called *expansion* of the graph.

Under either contraction or expansion, the total number of circuits in the graph is unchanged. Under contraction, both the number of vertices and the number of edges in the graph is reduced by the number of binary vertices.

A contracted graph, A^c, can be expressed in matrix form as follows:

$$a_{ij}^c = \begin{cases} k & \text{if vertex } i \text{ is connected to vertex } j \text{ by } k \text{ parallel edges} \\ 0 & \text{otherwise } (j = i \text{ included}) \end{cases} \tag{3.21}$$

Based on the definition of A^c given by equation (3.21), the row sum of any row is equal to the degree of the associated vertex. Because a contracted graph has no binary vertices, the minimum degree of any vertex is three.

3.2.6 - Relationship between Graph Theory and Effort Flow Analysis

One of the key motivations for representing product systems in a simplified schematic way is to promote the process of abstraction. Several possible abstract representation schemes exist for mechanical systems.

3.2.6.1 - Abstract Schematic Descriptions

One example is the *functional model (or function structure)* [1, 49, 52, 53, 87], which is a form-independent expression of the product design. The functional model is a domain independent network of functions representing all the necessary working principals needed to carry out the transformation of the physical flows from input to output.

Bond graphs represent another abstract representation of a physical system. The bulk of the research work carried out in synthesizing dynamic systems focuses on the use of bond graph methods [88-91], or equivalent, as the formal schematic description of a system being designed. By concentrating on the schematic description without regard to a physical description, the designer is forced to abstract the functional behavior of the product before worrying about its instantiation [50].

The schematic description developed for effort flow analysis is the effort flow diagram. Recall from the discussion on free-body diagrams and their correspondence to effort flow diagrams that the components of a product system are modeled as particles and the interfaces between interacting components are modeled as forces with sense, relative motion, and connectivity information content. These modeling simplifications lend themselves to description using the basic concepts from graph theory. Several examples exist for the use of graph theory in the schematic description of mechanical systems. Tsai uses graph theory to represent kinematic structures such as linkages and gear trains [86]. Steiner uses interaction graphs to model product connectivity [65]. Kusiak uses aspects of graph theory as a foundation for the automatic synthesis of component connectivity [92]. The precedent has been set for the use of graph theory as a basis for the schematic description of mechanical products, but several issues remain to be addressed.

3.2.6.2 - Representing Components and Interfaces

The primary issue is the way components and interfaces will be represented in the basis set of vertices and edges from graph theory. Components and interfaces can both be modeled as either vertices or edges. Effort flow analysis will use vertices to represent components and edges to represent interfaces. The rationale behind this decision is based partly on the examples cited in the literature from Tsai, Kusiak, and Steiner, which adds the benefit of a body of knowledge to support the use of graphs as a representation scheme in mechanical systems. Further reasons for the representation of components as nodes lie in the

modeling decisions made previously. Components are modeled as particles, which are represented as nodes in free-body diagrams and as nodes in the graphical representation used for the vertex in graph theory. There are compelling reasons to use edges to represent interfaces as well. In the graph theory representation of kinematic mechanisms, joints are represented as edges [86]. This representation logically leads to the use of the adjacency matrix to mathematically represent the connectivity of components within the system. Further support comes from the practice of labeling edges (joints) with the type of joint being represented (revolute, prismatic, gear pair, cam pair). This practice is analogous to labeling the edges (interfaces) in an effort flow diagram with the type of relative motion. Other utilitarian reasons exist for the use of graph theory to represent effort flow diagrams as well.

3.2.6.3 - Graph Theory as a Product Design Analysis Tool

The strength of representing a product as a connected graph is the insight into component interaction that emerges. One of the concepts that will be developed further in this dissertation is the identification of component combination opportunities based on particular graph structures. The graph theory concept that is most fundamental to the identification process is graph contraction. One of the hypotheses of this dissertation is that graph contraction is equivalent to component combination. An example of this process is discussed below. Two of the fundamental concepts in developing of an effort flow diagram are the effort flow direction (sense of the force), and the interaction of the product with the environment (e.g. support reactions). These two concepts find a clear foundation in the directed graph and the ground link respectively.

An additional use of the analytic power of graph theory is the use of graph trees. The relationship between graph trees and the current work is based on the existence of effort flow paths as serial relationships within effort flow diagrams. At least one serial path must exist between the applied external effort and the reaction effort at the supports or at the work piece within the system under investigation. Graphs also allow relatively simple identification of similarities between the component connectivity of product systems in very different product domains.

Another hypothesis of this dissertation is that effort flow analysis, and in particular the generation of effort flow diagrams, is a repeatable process. To test of the repeatability of constructing an effort flow diagram requires that similar diagrams be identifiable. The

adjacency matrix allows the comparison of different effort flow diagrams of the same product. Isomorphic Effort flow diagrams have the same adjacency matrix, thus a comparison of the rows gives insight into the repeatability of the method without comparing the diagrams as drawn by the engineer. To facilitate this approach, the vertices are labeled numerically before the test. By labeling components before hand, the vertex-numbering scheme will be standardized for all participants.

3.2.6.4 - Putting the Foundation Together: An Example

At this point, it is appropriate to bring together the foundations of effort flow analysis to represent a product. The examples will be presented without detailed explanation of the method, as that task is saved for a later chapter.

First, a simple example using Roberval's apparatus is shown in Figure 3.13. The components of the apparatus are massive bodies, massless strings and massless pulleys. These components are shown as free-bodies in the FBD, and as nodes in the effort flow diagram. The individual weights of the massive bodies are depicted as forces directed in line with the gravitational field and as efforts input to the bodies in the effort flow diagram. The support reactions between the pulleys and the ground are given as forces with unknown directions in the FBD's and are shown as effort flow to a ground link in the effort flow diagram. Finally, the interaction between the pulleys and the strings are shown on the FBD's as forces of unknown magnitude and direction, and as directed effort flows between the bodies in the effort flow diagram. The contribution of graph theory to this representation of Roberval's apparatus is the use of a directed graph as a common framework to depict the components and their interactions through the interfaces. Graph theory provides a consistent set of terms and mathematical techniques for the abstract representation and analysis of products.

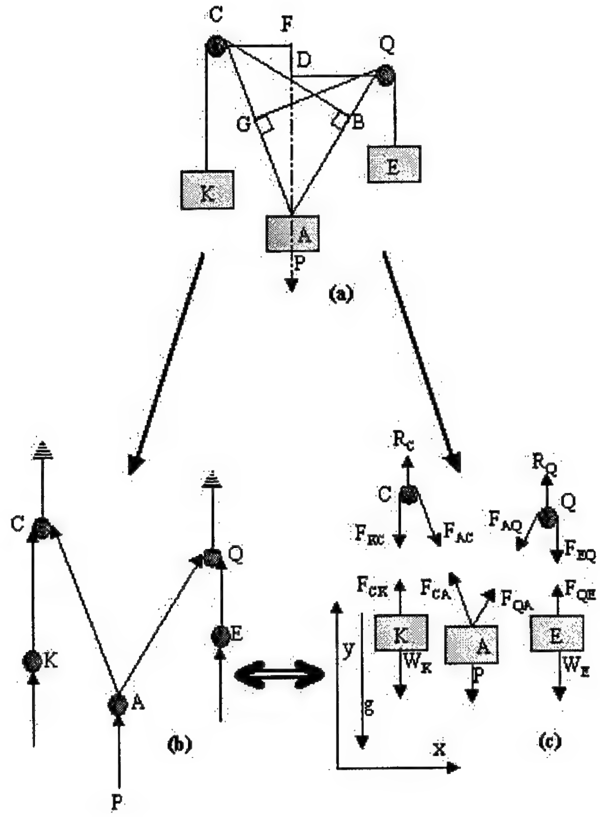


Figure 3.13: Equivalence of Free-Body Diagram (b) and Effort Flow Diagram (c) from Roberval's Apparatus (a)

As further evidence of the correspondence between the two models of the device, consider the equilibrium analysis application of Newton's laws to the individual bodies for Roberval's system. Take, for example, body **A:**

$$\begin{aligned} \sum F_x &= F_{QAX} - F_{CAX} = 0 \\ \sum F_x &= F_{QAY} + F_{CAY} - P = 0 \end{aligned} \tag{3.22}$$

The resulting vectors, $\mathbf{F_{CA}}$ and $\mathbf{F_{QA}}$ are equivalent in magnitude, direction, sense, and connectivity to the effort flows between body **A** and pulleys **C** and **Q** respectively.

The adjacency matrix for Roberval's apparatus is shown in Figure 3.14, the matrix shows that vertex **A** is connected to itself plus vertices **E** and **Q**, vertex **C** is connected to itself and vertices **A** and **K**, and so on for the rest of the system. The content of the adjacency

matrix depends only on the labeling and connectivity of the nodes and is independent of the way the effort flow diagram is drawn.

$$
\begin{array}{c}
 \\ a \\ c \\ e \\ k \\ q
\end{array}
\left.\begin{array}{c} \\ \\ \\ \\ \\ \end{array}\right\}
\begin{array}{c}
\overbrace{acekq} \\
\begin{bmatrix}
10101 \\
11010 \\
00101 \\
01010 \\
10101
\end{bmatrix}
\end{array}
$$

Figure 3.14: Adjacency Matrix for Roberval's Apparatus

Another simple demonstration of an effort flow diagram is the three-piece binder clip shown in Figure 3.15. In this case, operation being modeled is the opening of the binder clip. During this operation, the hand transfers force to each of the lever arms. These arms in turn transfer the force through the interface at the hinge joint to the clip. The effort flow diagram for this product is shown in Figure 3.16 where the adaptation of graph theory to represent the product is used. In this case, no work piece is present; hence, the effort flow goes into the clip and stops there. As stated earlier, the effort flow diagram is used as the tool within effort flow analysis the aids in identifying component combination opportunities.

(a)

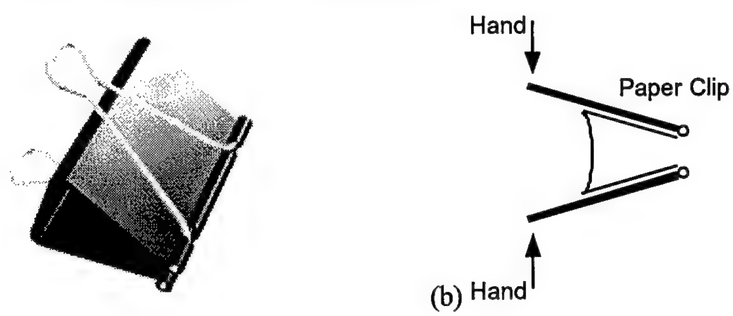


Figure 3.15: (a) Rendering of a Binder Clip (b) Model of a Binder Clip

If the effort flow diagram of Figure 3.16 is modified using the concept of graph contraction, where binary strings are contracted to a single node, the result is a single node. The single node incorporates both handles and the clip with which the hands will interface.

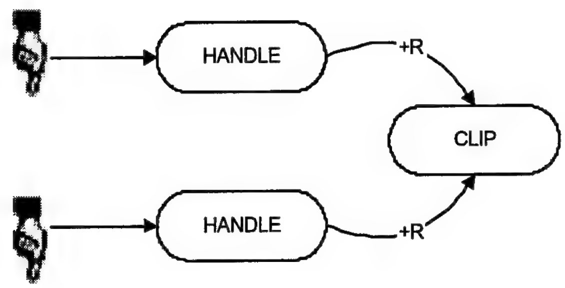


Figure 3.16: Effort Flow Diagram of Binder Clip

3.3 - Definitions for Effort Flow Analysis

Effort into a body is an effort applied to the body. Effort leaving a body is the effort supplied by the body of interest to another body in the network. The direction of the arrow indicates the flow of effort from the source to ground or the workpiece.

3.4 - Observations

The foundations of effort flow analysis have been explored via a survey of mechanics and the field of mathematics known as graph theory. Mechanics provides the framework for defining the fundamental relationships for components and their interactions. The correlation between the free-body diagram and the effort flow diagram is clearly established. Both models distill the complexity of the "real world" product down to an abstract physical model that contains only the elements essential to the analysis task. The second component in the foundation, graph theory, provides the framework for representing and analyzing the connectivity of the model. Graph theory provides a basis set of representation elements for the effort flow diagram. Additionally, adjacency matrix provides a convenient and standardized representation for component connectivity, and the relationship between graph trees and effort flow paths is established.

Chapter 4 - Effort Flow Analysis Fundamentals

4.1 - Introduction

The development of effort flow analysis as a design methodology has progressed from the humble beginnings of force flow through the establishment of a theoretical basis to the point here where the elements of a usable representation scheme can be developed. This chapter will freeze some concepts of the method at their current state in order that they may form the essential building blocks for the work that will follow. The elements presented here are advancements that have been made to the methodology, formal definitions, and the operational nomenclature of effort flow analysis. From these elements, a high level description of the overall methodology is constructed and presented with definitions for each process step. In the end, the insights gained from developing the methodology lead to the identification of latent shortcomings that motivate the work contained in the following chapters.

4.2 - Advancements to Effort Flow Analysis

4.2.1 - Importance of Relative Motion

Relative motion is defined as "a change in the position of a body or system with respect to time, as measured by a particular observer in a particular frame of reference. Only relative motion can be measured; absolute motion is meaningless" [93]. The study of relative motion as it pertains to components within a product is fundamental to the effort flow analysis methodology.

Lefever observed in the original work on force flow analysis [46] that the absence of macro scale relative motion is a marker for component combination opportunities. It is proposed in Chapter 2 that focusing on the absence of macro scale relative motion is too limiting a view. In this section it is proposed that the existence of relative motion in varying degrees is *the primary indicator* of component combination opportunities in effort flow analysis. The basis for this statement is that relative motion implies the association between the forces of interaction and energy or power flow in a system. This hypothesis is supported by observations about the importance of relative motion in both physical systems modeling and functional modeling.

4.2.1.1 - Energy Considerations

In modeling energetic physical systems using power flow theories such as Bond Graphs [94, 95], power is the entity of primary interest. Power is the product of effort and flow, and, in mechanical systems effort equates to force or torque, and flow equates to velocity. In functional modeling using the theory of technical systems, energy, or power, is one of the triad of fundamental "functional flows," namely: material, energy, and information [49]. In the mechanical domain, modeling of the energy flow requires, at a minimum, the presence of a force and may include a velocity as well. In representing the mechanical domain using either the power flow of a bond graph or the energy flow of a functional model, the fundamental variables are force (or torque), and velocity.

Like power flow analysis and functional modeling, effort flow analysis in the mechanical domain focuses on the flow of effort (force or torque) through the product of interest. The presence of effort in a mechanical product is invariably accompanied by relative velocity between components during some aspect of product operation. The presence of effort is a fundamental requirement for effort flow analysis, while the presence of relative velocity is not. However, the presence of relative motion is critically important from the standpoint of highlighting the locations of interesting interactions between components in the system.

4.2.1.2 - Basis Set for Relative Motion

The characterization of relative motion is studied in several areas of engineering design [65, 86, 91, 96, 97], and is of particular interest in effort flow analysis. The fundamental information needed to apply effort flow analysis to product evolution is captured in the interface description, and is represented in the effort flow diagram by the links and their labels. The interface information set includes, at a minimum, the interface characterization, the direction of the effort flow, and the operation with which the effort is associated. The interface characterization is based on the type of relative motion that exists between the connected components. There are a limited number of relative motion types in effort flow analysis, and Table 4.1 captures the possible permutations as well as a naming convention adopted to describe them. Because this set contained in Table 4.1 spans all possible combinations of relative motion in the mechanical domain, and because the members

of this set are orthogonal, the set is referred to as an *effort flow analysis relative motion basis,* or simply the relative motion basis from this point forward.

Table 4.1: Table of Relative Motion Permutations

Link Type	**Relative Motion Location**	
	Between Interfaces	**Between Components**
N-Link	**0**	**0**
C-Link	**0**	**1**
R-Link	**1**	**1**
I-Link	**1**	**0**

4.2.1.3 - Effort Flow Analysis Link Types

Four flow links are now possible, and these links between connected components are defined as follows:

"N-Link": No relative motion between components.

"C-Link": Relative motion between the non-interfacial regions of components.

"R-Link": Relative motion at the interface and between other regions.

"I-Link": Relative motion at the interface only. (It should be noted that this type of interface has not been observed in any device from the mechanical domain, but is included in the basis set for completeness.)

This new characterization of relative motion leads to a more refined set of criteria for investigating component combination possibilities.

As stated earlier, the interface holds a special place in the effort flow analysis method. The interface is where relative motion is delineated, and as such identifies locations within the product model where something interesting is happening. Hence, relative motion represents an easily identifiable characteristic of component interaction and provides a convenient classification scheme for cataloging component combination opportunities for products from the mechanical domain. At this point in the discussion, it is appropriate to define some of the types of effort flows that can transit an interface.

4.2.2 - Degrees-of-Freedom

The presence of motion within a device implies that a function is being provided by the components of that device. From the functional basis developed by Stone [54], and later

reconciled by Hirtz [98], it is apparent that there are a limited number of basis functions specifically concerned with providing relative motion in a product. Those basis functions are: Guide, Translate, Rotate, and Allow DOF. Another possibility is that motion is prevented, in which case, several more basis functions can be added to the list: Actuate, Stop, Prevent, Inhibit, Secure, and Position. The former set of basis functions are provided using component interfaces that are characterized either as a C-Link or as a R-Link, while the latter functions are provided by the any of the link types, N-Link, R-Link, and C-Link.

Regardless of the type of link or component under consideration, the overall function providing degrees-of-freedom (DOF) of the original system must be maintained. The exception to this occurs when a DOF is removed to satisfy a customer need with a higher importance. The DOF of a system represent the number of independent parameters needed to completely describe the configuration of the mechanism in space. On a more intuitive level, the degrees-of-freedom are the sum of the DOF over all the components in a product reduced by the total number of degrees of constraint over all the joints in the product. One of the methods of for determining the degrees-of-freedom used in mechanism analysis is the *Grübler* criterion.

$$F = \lambda(n - j - 1) + \sum f_i \tag{4.1}$$

f_i: degrees of relative motion permitted by joint i.

j: number of joints in the system.

n: number of links in the system, including the ground link.

λ: degrees-of-freedom of the space in which the system is intended to function. For spatial mechanisms, λ=6 and for planar and spherical mechanisms, λ=3.

The result of applying the *Grübler* criterion, Equation 4.1, is the total number of degrees-of-freedom for the system. In the context of effort flow analysis, the degrees-of-freedom represent the motion that a component is free to assume within a reference frame, that motion may be any of the following:

Translation in X
Translation in Y
Translation in Z
Rotation about X: Roll
Rotation about Y: Pitch
Rotation about Z: Yaw.

It should be noted that the names of the axes are completely arbitrary, and the origin may be inertial or in motion with the product or one of its components. The information on degrees of freedom is normally annotated only on the most specific forms of the effort flow diagram where the diagram is being refined.

Now that the relative-motion, energy, and DOF fundamentals behind the effort flow analysis method are established, it is now possible to use those fundamentals to define the representational elements used to construct an effort flow diagram.

4.3 - Definitions of the Graphical Elements

The foundation for effort flow diagrams as abstract graphical product models is established in Chapter 3, while the aim of this section is to build upon the mechanics and graph theories to develop and define the individual elements that make up the effort flow diagram. The graph elements are the building blocks of graphical representation in effort flow analysis. First, the Nodes, which represent the components, are described, and then the Links, which represent the interfaces between the components, are described.

4.3.1 - Nodes

Components are represented as nodes in effort flow analysis. In the effort flow diagram, nodes are symbolized as annotated ellipses. Three types of nodes are used to model components in effort flow analysis. These types are: component, functional component, and workpiece. Each of the three node types is shown in Figure 4.1, and described in the sections that follow.

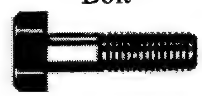
NODES			
Element	**Description**	**Example**	**Nature**
1 - COMPONENT	Component internal to the system of interest	Bolt 	Teeth
1 - FUNCTIONAL COMPONENT	A portion of a monolithic component that performs a specific function	Flexible Joint 	Stomach within the digestive system
WORKPIECE - OBJECT	The object on which the product operates	Aluminum Sheet 	Food being chewed

Figure 4.1: Node Representations

4.3.1.1 - Component

The components of a product are the fundamental entities that a designer uses to model and represent artifacts in effort flow analysis. A node may represent a single component, or it may represent a collection of components that form a subassembly or module. When used for sub-assemblies or modules, the nodal representation indicates that the entity is not available for further decomposition. An example might be a motor that is purchased from a vendor and is not subject to redesign in the current design effort. Components are depicted on the effort flow diagram as nodes, where the definition of a node is presented in the section of Chapter 3 that details graph theory and its relationship to effort flow analysis.

Each individual part of the product is named and numbered. Node numbering is done to facilitate storage of component connectivity information using an adjacency matrix as previously discussed in the Graph Theory section of Chapter 3. Component naming is based, when possible, on the most common name available for a particular component. The naming

convention used may be internal to the company or one established by industry standards and practices. A naming convention is proposed as part of the work of this dissertation, and is contained in Appendix A. Appendix A presents a basis set of component names that can be used to describe components or collections of components from the domain of mechanical effort transmitters.

An alternative to using plain language names is to use a numbering scheme for the components of a product. Numbering components simplifies the task of computationally manipulating components in applications such as automated synthesis of design variants [91, 99, 100]. Independent of the naming scheme used, plain language or numbered, the components of a product will have interfaces with one another, and with the environment, and those interfaces must be identified.

4.3.1.2 - Functional Component

Functional components are an abstraction of the *component.* Functional components highlight the existence of function sharing within a component by decomposing the function-sharing component into separate nodes. The separate nodes represent the regions of the original component that are responsible for providing the individual functions. With highly function-shared components, the aim is to show the relationship between component features and their contribution to overall product functionality. Hence, the functional component allows the function sharing to be modeled as separate nodes that represent functionally independent regions of the component. These separate nodes are then connected by links that represent the interaction at the interfaces between the functional components.

The existence of a functional component or function sharing is may be evidenced by a change in the effort-flow as it transits the component. For example, when an effort-flow enters as a N-Link, and leaves as a R-Link, this change in the flow indicates the presence of function-sharing in the component that implemented that change. To achieve a change in the effort flow, the component must enable a change in the DOF for the motion. Functional components in the mechanical domain are often associated with the Allow DOF function from the functional basis [54, 98].

Functional components are useful for modeling several types of components. For example, a product that has undergone previous combination or a component that is resistant to combination because of a design conflicts would be a candidate for modeling as a set of

functional components. For highly function-shared products, the effort flow diagram can be so simple that they provide very little useful insight into the product and associated components. Functional components allow the designer to extract individual functional components from a contracted product to allow for different redesign opportunities.

In applying functional components as a product decomposition tool, only those features that map directly to functions represented in the functional model are included in the effort flow diagram. This approach strengthens the relationship between the effort flow diagram and the functional model for a product. The naming convention used for functional components is based on the name of the feature that gives rise to the function, for example bosses, hinges, and collars are all appropriate names for a functional component. This approach is consistent with the naming convention used to name the other nodes in the model.

4.3.1.3 - Workpiece

Many products are designed to operate on an artifact; that is, to do useful work on an object. In functional modeling, a physical object that is operated on by the product of interest is classified as a *material flow* [49]. Effort flow analysis captures the interaction between the product and the material flow using a special class of component known as a *workpiece*. For products that do work on objects, modeling the nature of the interaction between the two is critical in understanding the overall operation of the product. For this reason, whenever there is a workpiece associated with the product, it must be included in the effort flow analysis. Although the *workpiece* is represented as a component of the system, the workpiece is not generally considered combinable with other components in the product.

4.3.2 - Links

In effort flow analysis, interfaces are modeled as links and graphically represented as a directed arrow with annotation. It is important to have a clear definition of what is meant by an interface. In this dissertation, an interface is defined as:

A spatial region where energy and/or material flow exists between components or between a component and the external environment [8].

Note that this definition of an interface does not include or require the detailed spatial or structural aspects that have been included by other researchers [65, 101]. While it is true

that a highly detailed interface description is important in general design analysis, it is not warranted to meet the goal of effort flow analysis, which is to describe as simply as possible the existence and fundamental characteristics of component interaction as effort is transmitted through the interface.

Satisfaction of the goal of identifying and characterizing interfaces in as simple a manner as possible leads to two classes of interfaces. The two classes of links are those that are internal to the system boundary and those that cross the system boundary. The internal links are derived from the basis for relative motion in effort flow analysis discussed previously. The four link types are explained in more detail in this section. The graphical representation of each of the link types is shown in Figure 4.2, along with the DOF associated with each and examples of engineered and natural occurrences of each.

4.3.2.1 - The Non-Relative Motion Link: "N-Link"

A N-Link represents interaction where there is no relative motion between any regions of the connected components. In mechanics, this type of motion is referred to as rigid body motion, meaning that the components follow the generalized form of Newton's second law of motion. The degrees of freedom for an N-Link are zero; this means the state in space of one component is completely described by the state of the component with which it is connected via the N-Link. The energy associated with the N-Link is the kinetic energy due to the rigid body motion of the components.

4.3.2.2 - The Component Relative Motion Link: "C-Link"

A C-Link represents interaction between components where there is relative motion between the extents of the components but no relative motion at the interface. This implies deformation of one or both of the components as forces are transmitted. C-Links may represent either elastic or plastic behavior in the interfacing components. For example, components that experience single or multi-cycle plastic deformation can represent a C-Link just as well as a spring can.

Deformation implies that some number of degrees-of-freedom exist for components connected by a C-Link. Description of the position in space of a compliant component is, in general, more difficult than for rigid members. For example, the analysis of a simple fixed-free beam requires that differential equations be used to describe the behavior of any point

opportunities for products from the mechanical domain. At this point in the discussion, it is appropriate to define some of the types of effort flows that can transit an interface.

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The presence of motion within a device implies that a function is being provided by the components of that device. From the functional basis developed by Stone [54], and later reconciled by Hirtz [98], it is apparent that there are a limited number of basis functions specifically concerned with providing relative motion in a product. Those basis functions are: Guide, Translate, Rotate, and Allow DOF. Another possibility is that motion is prevented, in which case, several more basis functions can be added to the list: Actuate, Stop, Prevent, Inhibit, Secure, and Position. The former set of basis functions are provided using component interfaces that are characterized either as a C-Link or as a R-Link, while the latter functions are provided by the any of the link types, N-Link, R-Link, and C-Link.

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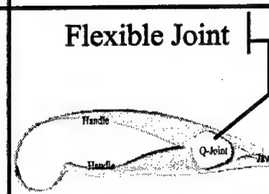
NODES			
Element	Description	Example	Nature
1 - COMPONENT	Component internal to the system of interest	Bolt 	Teeth
FUNCTIONAL COMPONENT	A portion of a monolithic component that performs a specific function	Flexible Joint 	Stomach within the digestive system
WORKPIECE - OBJECT	The object on which the product operates	Aluminum Sheet 	Food being chewed

Figure 4.1: Node Representations

4.3.1.1 - Component

The components of a product are the fundamental entities that a designer uses to model and represent artifacts in effort flow analysis. A node may represent a single component, or it may represent a collection of components that form a subassembly or module. When used for sub-assemblies or modules, the nodal representation indicates that the entity is not available for further decomposition. An example might be a motor that is purchased from a vendor and is not subject to redesign in the current design effort. Components are depicted on the effort flow diagram as nodes, where the definition of a node is presented in the section of Chapter 3 that details graph theory and its relationship to effort flow analysis.

Each individual part of the product is named and numbered. Node numbering is done to facilitate storage of component connectivity information using an adjacency matrix as previously discussed in the Graph Theory section of Chapter 3. Component

naming is based, when possible, on the most common name available for a particular component. The naming convention used may be internal to the company or one established by industry standards and practices. A naming convention is proposed as part of the work of this dissertation, and is contained in Appendix A. Appendix A presents a basis set of component names that can be used to describe components or collections of components from the domain of mechanical effort transmitters.

An alternative to using plain language names is to use a numbering scheme for the components of a product. Numbering components simplifies the task of computationally manipulating components in applications such as automated synthesis of design variants [91, 99, 100]. Independent of the naming scheme used, plain language or numbered, the components of a product will have interfaces with one another, and with the environment, and those interfaces must be identified.

4.3.1.2 - Functional Component

Functional components are an abstraction of the *component*. Functional components highlight the existence of function sharing within a component by decomposing the function-sharing component into separate nodes. The separate nodes represent the regions of the original component that are responsible for providing the individual functions. With highly function-shared components, the aim is to show the relationship between component features and their contribution to overall product functionality. Hence, the functional component allows the function sharing to be modeled as separate nodes that represent functionally independent regions of the component. These separate nodes are then connected by links that represent the interaction at the interfaces between the functional components.

The existence of a functional component or function sharing is may be evidenced by a change in the effort-flow as it transits the component. For example, when an effort-flow enters as a N-Link, and leaves as a R-Link, this change in the flow indicates the presence of function-sharing in the component that implemented that change. To achieve a change in the effort flow, the component must enable a change in the DOF for the motion. Functional components in the mechanical domain are often associated with the Allow DOF function from the functional basis [54, 98].

Functional components are useful for modeling several types of components. For example, a product that has undergone previous combination or a component that is resistant to combination because of a design conflicts would be a candidate for modeling as a set of functional components. For highly function-shared products, the effort flow diagram can be so simple that they provide very little useful insight into the product and associated components. Functional components allow the designer to extract individual functional components from a contracted product to allow for different redesign opportunities.

In applying functional components as a product decomposition tool, only those features that map directly to functions represented in the functional model are included in the effort flow diagram. This approach strengthens the relationship between the effort flow diagram and the functional model for a product. The naming convention used for functional components is based on the name of the feature that gives rise to the function, for example bosses, hinges, and collars are all appropriate names for a functional component. This approach is consistent with the naming convention used to name the other nodes in the model.

4.3.1.3 - Workpiece

Many products are designed to operate on an artifact; that is, to do useful work on an object. In functional modeling, a physical object that is operated on by the product of interest is classified as a *material flow* [49]. Effort flow analysis captures the interaction between the product and the material flow using a special class of component known as a *workpiece*. For products that do work on objects, modeling the nature of the interaction between the two is critical in understanding the overall operation of the product. For this reason, whenever there is a workpiece associated with the product, it must be included in the effort flow analysis. Although the *workpiece* is represented as a component of the system, the workpiece is not generally considered combinable with other components in the product.

4.3.2 - Links

In effort flow analysis, interfaces are modeled as links and graphically represented as a directed arrow with annotation. It is important to have a clear definition of what is meant by an interface. In this dissertation, an interface is defined as:

A spatial region where energy and/or material flow exists between components or between a component and the external environment [8].

Note that this definition of an interface does not include or require the detailed spatial or structural aspects that have been included by other researchers [65, 101]. While it is true that a highly detailed interface description is important in general design analysis, it is not warranted to meet the goal of effort flow analysis, which is to describe as simply as possible the existence and fundamental characteristics of component interaction as effort is transmitted through the interface.

Satisfaction of the goal of identifying and characterizing interfaces in as simple a manner as possible leads to two classes of interfaces. The two classes of links are those that are internal to the system boundary and those that cross the system boundary. The internal links are derived from the basis for relative motion in effort flow analysis discussed previously. The four link types are explained in more detail in this section. The graphical representation of each of the link types is shown in Figure 4.2, along with the DOF associated with each and examples of engineered and natural occurrences of each.

4.3.2.1 - The Non-Relative Motion Link: "N-Link"

A N-Link represents interaction where there is no relative motion between any regions of the connected components. In mechanics, this type of motion is referred to as rigid body motion, meaning that the components follow the generalized form of Newton's second law of motion. The degrees of freedom for an N-Link are zero; this means the state in space of one component is completely described by the state of the component with which it is connected via the N-Link. The energy associated with the N-Link is the kinetic energy due to the rigid body motion of the components.

4.3.2.2 - The Component Relative Motion Link: "C-Link"

A C-Link represents interaction between components where there is relative motion between the extents of the components but no relative motion at the interface. This implies deformation of one or both of the components as forces are transmitted. C-Links may represent either elastic or plastic behavior in the interfacing components. For example, components that experience single or multi-cycle plastic deformation can represent a C-Link just as well as a spring can.

Deformation implies that some number of degrees-of-freedom exist for components connected by a C-Link. Description of the position in space of a compliant component is, in general, more difficult than for rigid members. For example, the analysis of a simple fixed-free beam requires that differential equations be used to describe the behavior of any point along the beam. This becomes especially difficult for materials that do not exhibit linear deflection behavior.

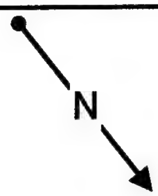
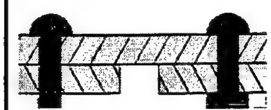
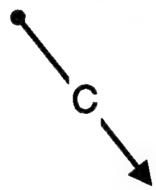
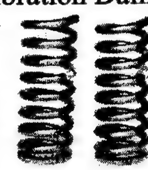
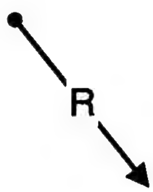
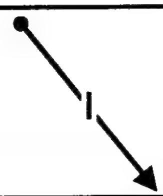
INTERNAL LINKS			
Element	**DOF**	**Engineered**	**Natural**
	$\begin{bmatrix}0\\0\\0\\0\\0\\0\end{bmatrix}$	Riveted Joint 	Rocks in a formation. Uncommon in biological structures.
	$\begin{bmatrix}x\\y\\z\\roll\\pitch\\yaw\end{bmatrix}$	Coil Spring, Vibration Damper, 	Ligament, Tree Trunk in Ground, Boundary Layer Flow. Most common biological interface
	$\begin{bmatrix}x\\y\\z\\roll\\pitch\\yaw\end{bmatrix}$	Revolute, Spherical, and Prismatic Joints 	Elbow, Finger, Knee
	$\begin{bmatrix}?\\?\\?\\?\\?\\?\end{bmatrix}$	None	None

Figure 4.2: Internal Link Representations

The effort flow associated with a C-Link is the result of a composite of both kinetic and potential energies. The kinetic energy arises from the motion of the component and the potential energy from the strain due to deformation of the component. A simplified analysis technique known as the pseudo rigid-body model is proposed by Howell [29]. In pseudo-rigid body approach, the flexible member is modeled as a system composed of two rigid members linked by a pin joint. The strain energy stored in the deflected component is modeled as a torsional spring. This modeling simplification allows the flexible member to be analyzed using techniques from rigid body mechanisms.

Assuming the simplifications associated with the pseudo-rigid body model are acceptable, the DOF for a compliant member can be represented in a simplified manner using Equation 4.1, otherwise the DOF definition is less well behaved.

4.3.2.3 - The Relative Motion Link: "R-Link"

A R-Link represents relative motion both at the interface and between components. The DOF for the R-Link may include any of the six variables described previously (*x, y, z, roll, pitch, yaw*), and the components may, in general, be either rigid or compliant. The possibility of flexibility in the components compounds the complexity of describing the position of a body for the reasons discussed in the section on C-Links. The effort flowing through the interface represented by the R-Link is again the result of a composite of kinetic and potential energies.

4.3.2.4 - The Interface Relative Motion Link: "I-Link"

An I-Link represents relative motion at the interface only. While clearly a member of the basis set, this permutation of the relative motion combinations has not appeared in any of the mechanical domain products observed in this research effort. Further discussion of the I-Link will be set-aside until other energy domains are investigated as part of a future work

4.3.3 - External Links

External links represent the interfaces between the product and the external environment. External links model efforts that cross the system boundary as either *applied* or *resultant* flows. The *applied* external effort flows are the forces, torques and moments applied to the product to initiate or complete desired operations. The *resultant* external effort flows are the forces, torques and moments that arise between the product and the environment because of the applied efforts. These may include support reactions, interactions with a workpiece, or other environmental interactions. Accurate accounting of external efforts is critical to successful mapping of the effort flows through the product. If the external sources of effort are not accurately identified and located, then the internal mapping will not be accurate, resulting in a loss of fidelity.

Three classes of external links exist within the effort flow analysis domain. The external link classes are *general external link, human external link,* and *ground link*, the last two classes being specific cases of the *general external link* class. Because these links represent the interactions of the product with its surroundings, the nature of the relative motion at the interface is not treated. These links are at the system boundary and do not, in general, represent an opportunity for component combination. For example, a handle would not be considered for combination with the hand that grasps it. Examples of external inputs include the application of motive power, human forces, wind loads, gravity, etc. The external link representations are shown in Figure 4.3, and described in the sections that follow.

4.3.3.1 - General External Link

The general external link represents interaction between a component and an effort source that is outside the system boundary. The relative motion for this link is <u>not</u> characterized, only the operation and the direction are annotated in the link label.

One special case from this link class is the effort applied to a product by an internal *power source*. Examples of power sources include electric motors, internal combustion engines, and other types of self contained mechanical energy sources that are typically found inside the product boundary. The true source of effort for these devices is generally external to the system. These effort sources are treated as modules or components of the product that may be candidates for combination, but their internal operation is not modeled in the analysis unless the designer has the ability to affect change on their internal constitution.

As an example, consider an electric powered machine tool, the effort generated by the electric motor is the result of electric current flowing across the system boundary via the power cord. The true source of the effort is the current that crosses the system boundary, but that current (and voltage) is transformed into a mechanical torque by the motor. Effort flow analysis in the mechanical domain accounts for this electric effort source as a general external effort flow interfacing with the motor. The mechanical effort that results from the motor is then treated as a normal internal effort flow between the motor and the components with which it interfaces.

4.3.3.2 - Human External Link

The human external link represents the transmission of effort due to interaction between a human operator and any component of the product. The human external link takes its special classification from the fact that when a machine must interface with a human operator, the human interface becomes a critical element in the design of that machine. In addition, because the human is not generally considered as a candidate for component combination, the type of relative motion for this link is <u>not</u> treated; only the operation and direction are annotated in the link label.

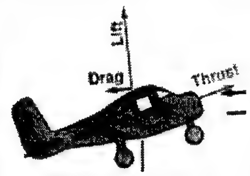
EXTERNAL LINKS			
Element	**Description**	**Engineered**	**Natural**
	General External Link	Aerodynamic Loads 	Wind Loading on a tree. Gravitational pull.
	Human External Link	Thumb 	Grasping an object
	Ground Link	Base Support 	Roots of a Tree

Figure 4.3: External Link Representations

4.3.3.3 - Ground Link

The ground link represents interaction between a component and a support or ground. The ground link is a unique type of external input, as it represents the interaction and interface between the product and its ground support structure. Not all products have

this type of interaction, hand held products are one example. The ground link assumes its special classification from the representation of mechanisms using graph theory, where the graph structure used to represent a grounded mechanism is known as a *rooted graph* [86]. For a more in-depth discussion of the ground link, see the graph theory section of Chapter 2. Like the human external link, the relative motion for the ground link is not treated; only the operation and direction are annotated in the link label.

4.3.4 - User Operations

Another of the modeling considerations that must be made during the process of applying effort flow analysis is to consider the way the product will be used. This determination is made using the stated customer needs then generating an activity diagram based on those customer-needs [1]. The activity diagram is defined as; "A network layout of sequential and parallel tasks carried out by the user." The activity diagram chronicles high level user activities associated with a product from cradle to grave. The activities of interest can be associated with users at various stages in the product life cycle. Examples of users include assemblers, consumers, maintainers, and recyclers.

The activities depicted on the diagram are initially very high level, as an activity is chosen for study, the detail can be increased to account for the specific operations of that activity. An example of an activity diagram is shown in Figure 4.4, where the activities associated with an ice cream scoop are shown. Note that the level of detail used for the Assemble, Transport, Display, and the Disposal activities is minimal, while the activities associated with the consumer operations are given in more detail. This increased detail represents a decision on the part of the designer to focus on a particular set of operations during effort flow analysis.

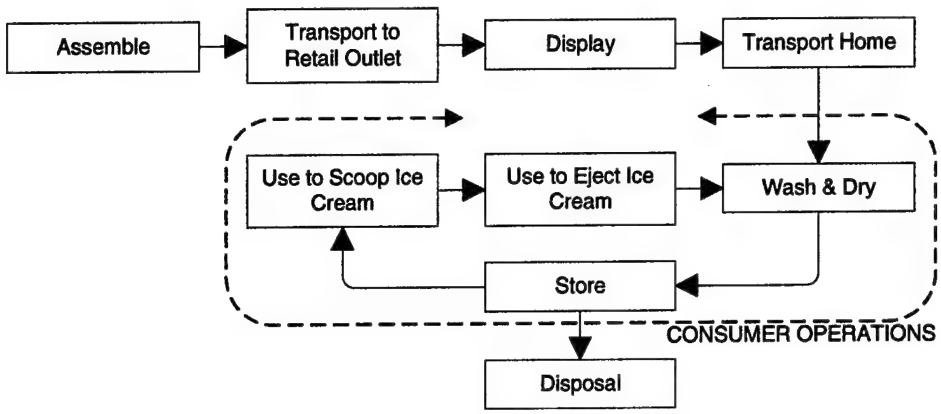


Figure 4.4: Ice Cream Scoop Activity Diagram

The relationship between the activity diagram and effort flow analysis becomes apparent when deciding how to model the effort flows associated with the operations performed by the user. In general, each operation will have a set of external inputs associated with it. These distinct external inputs will generate distinct internal effort flows within the product. The modeling of these distinct flows leads to the identification of product evolution opportunities. At the point where the operations to be modeled have been decided, the question of how to represent these flows in the effort flow diagram becomes an issue.

There are two approaches to graphically representing the flows associated with multiple operations; namely the discrete approach and the aggregate approach. In the *discrete* approach, the flows from the individual operations are modeled on separate effort flow diagrams. For products with a small number of operations, the result is a small set of diagrams that can be analyzed individually to identify opportunities for product evolution. The discrete approach is appropriate when the objective is to evolve the components associated with a single operation. The discrete approach is also useful when the resulting graphs exhibit little interaction between the flows of different operations. Two propositions are made regarding discrete effort flow diagrams and their graph structure.

PROPOSITION 4.1: If modeling an operation leads to an effort flow diagram where all the links are distinct, then the effort flow diagram represents a *trail* (all the edges are distinct).

The importance of Proposition 4.1 is that if the links are distinct, then manipulation of the interfaces associated with one user operation will not generally affect other user operations.

PROPOSITION 4.2: If modeling an operation leads to an effort flow diagram where all the links and all the nodes are distinct, then the effort flow diagram represents a *path* (all edges and vertices are distinct).

The importance of Proposition 4.2 is that if the links and nodes are distinct, then the components do not interact during any of the operations being modeled and hence product evolution for any flow is independent of the other flows. Both of these observations are examples of the independence axiom from axiomatic design [10].

The discrete approach is not well suited for cases where multiple operations are active over each of the individual flows in the diagram, the difficulty is that the interaction between operations is lost because each link has at most one active operation. The insights gained from multiple flows on a single link is completely masked in the discrete approach. When multiple operation links are prevalent, the more appropriate effort flow diagram approach is to model the operations of the product in an aggregate diagram.

In the *aggregate* approach, all the operations of interest and their resulting flows are modeled on the same effort flow diagram. This approach is analogous to the technique from functional modeling where each customer need is analyzed individually leading to functional models for each of the customer needs. The separate models are then aggregated into a consolidated functional model of the product for the known customer needs [1, 56].

PROPOSITION 4.3: If the aggregate model of the operations of the product leads to an effort flow diagram where every node is connected to every other node,

then the effort flow diagram represents a *connected graph* (every vertex in the graph, ***G***, is connected to every other vertex in ***G*** by at least one path).

The importance of Proposition 4.3 is that if the effort flow diagram is a connected graph, then a change to any one component will directly affect every other component. The connected graph is the antithesis of Suh's independence axiom [10].

An unavoidable side effect of modeling multiple operations on one diagram is that an aggregate diagram becomes congested. Many of the interfaces will transmit effort for more than one operation leading to multiple links at a single interface. Unfortunately, it is essential that the interactions of all the operations be captured in order to make decisions about the feasibility of proposed design changes. Overcoming the difficulties associated with the aggregate approach is identified as one of the areas in need of attention in this research effort. The efforts taken to reduce complexity are discussed in the next section.

4.3.5 - Reducing Diagram Complexity

One measure of diagram complexity is the total number of links between nodes. In order to reduce this complexity metric, only one link per physical interface is used for all operations modeled in the diagram. This single link per interface dictates that the link labels convey information on the relative motion characterization, the operation associated with the characterization, and the direction of the effort flow relative to that indicated by the single link. The trade-off is an increase in the notational density of each link in order to reduce the complexity of the overall diagram layout. The combined user operation and link characterization label are as constructed as follows: $\mathbf{N}_{\pm1,\pm2,\ldots,\pm n}$, $\mathbf{C}_{\pm1,\pm2,\ldots,\pm n}$, $\mathbf{R}_{\pm1,\pm2,\ldots,\pm n}$, and $\mathbf{I}_{\pm1,\pm2,\ldots,\pm n}$. The nomenclature of these links is described in Table 4.2, where *N, C, R,* and *I* represent the interface relative motion characterization; $\pm$ indicates the flow direction relative to the single reference link; and *1,2,...,n* represent the operation number.

An example of the change in diagram complexity that is achieved through this change in nomenclature is shown in the changes between Figure 4.6 and Figure 4.7. The diagram shown in Figure 4.6 is a model of a spring powered toy car, where each active operation has its own interface link. The links are color coded for the operation with

which it is associated as shown in the legend of the figure. In all, there are four operations using 98 individual links to connect 19 components in Figure 4.6. Contrast this with the same product modeled in Figure 4.7, where 30 individual links are able to model the same number of components, operations, and interfaces. The result is a nearly 67% reduction in the complexity of the diagram.

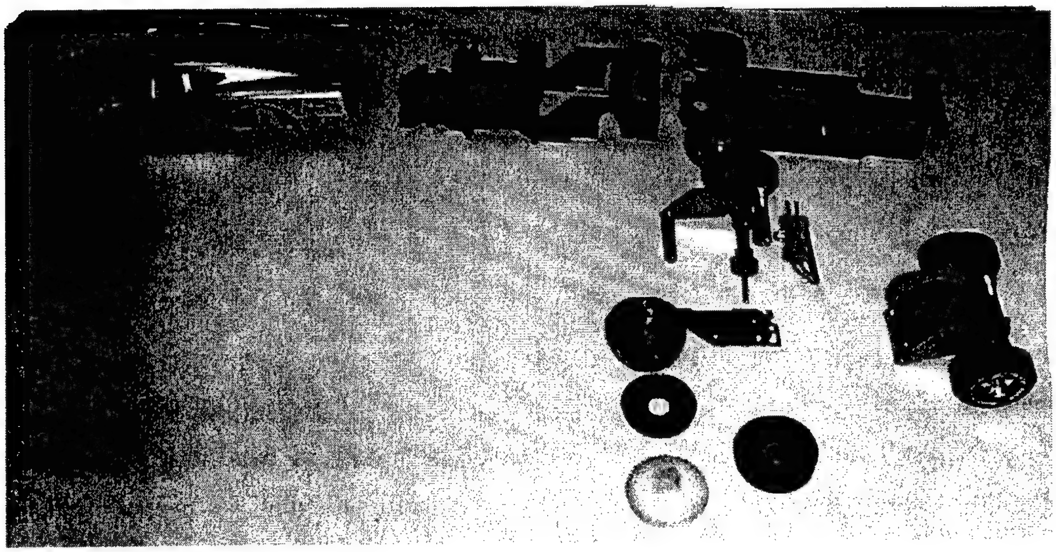


Figure 4.5: Exploded View of a Darda Car

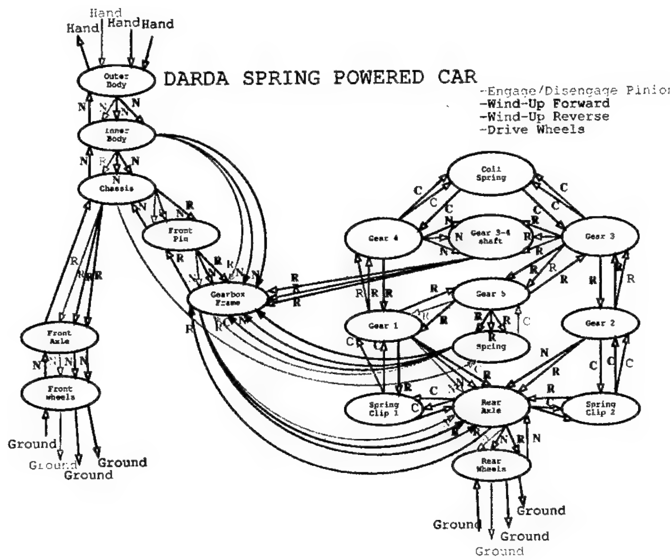


Figure 4.6: Effort Flow Diagram of a Spring Powered Car

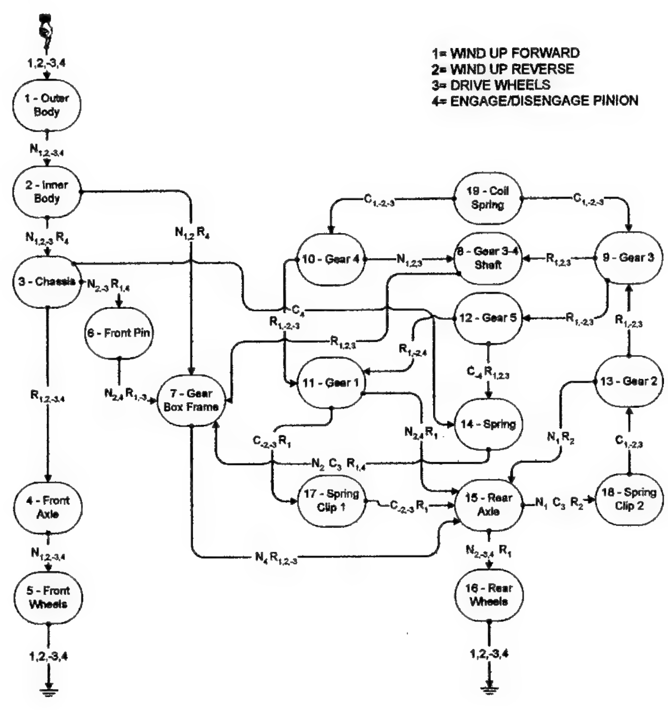


Figure 4.7: Simplified Effort Flow Diagram of a Spring Powered Car

4.3.6 - Effort Flow Diagram Nomenclature

As the diagram complexity is reduced, the information contained in the diagram must be conveyed using a more compact labeling notation. The elements that make up this notation for the links are shown in Table 4.2 and Table 4.3, and for the nodes in Table 4.4. Each of the effort flow diagram entities contained in the tables are a variation on the links or the nodes first introduced at the beginning of this chapter.

The most notable variation in the depiction is the link with the double-headed arrow. The double-headed arrow is standard notation for torque in free-body-diagrams, and has been adopted in effort flow analysis to denote effort flows that are either torques or moments. In the description of the links, the sign of the operation number is mentioned but not depicted in the symbol column of Table 4.2 and Table 4.3. The sign is omitted purposely from the label. The only sign that will be included in the label is the negative sign (-), the positive sign is assumed. The negative sign indicates that the flow of effort for that operation number is in the opposite direction from the reference link drawn in the diagram. An example of this simplified notation is shown in Figure 4.7, contrast this with the original approach as shown in Figure 4.6.

Table 4.2: Effort Flow Diagram Internal Link Nomenclature

INTERNAL LINKS		
ENTITY	SYMBOL	BRIEF DESCRIPTION
N-Link	$N_{1,2,3...}$ $N_{1,2,3...}$	N = No Relative Motion 1,2,3,... = Operation Number Sign of 1,2,3,... = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
C-Link	$C_{1,2,3...}$ $C_{1,2,3...}$	C = Component Relative Motion 1,2,3,... = Operation Number Sign of 1,2,3,... = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
R-Link	$R_{1,2,3...}$ $R_{1,2,3...}$	R = General Relative Motion 1,2,3,... = Operation Number Sign of 1,2,3,... = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
I-Link	$I_{1,2,3...}$ $I_{1,2,3...}$	I = Interface Relative Motion 1,2,3,... = Operation Number Sign of 1,2,3... = Flow Direction relative to arrow. Single Arrow Head = Force

Table 4.3: Effort Flow Diagram External Link Nomenclature

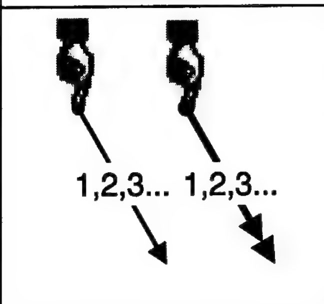
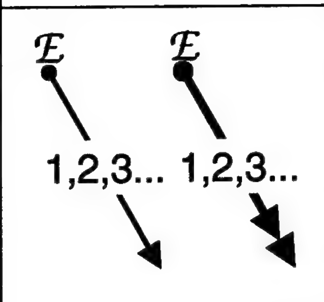
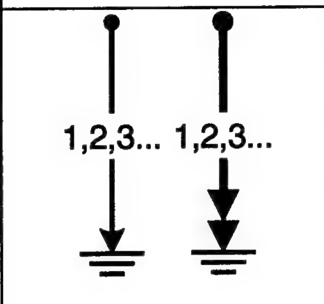
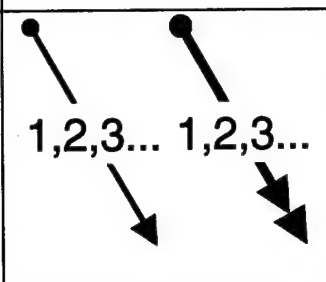
EXTERNAL LINKS		
ENTITY	SYMBOL	BRIEF DESCRIPTION
Human External Effort		Hand = Human Effort 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
General External Effort		$\mathcal{E}$ = External Effort 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
Ground Link		SYSTEM TO GROUND LINK 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
Workpiece Link		SYSTEM TO WORKPIECE LINK 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque

Table 4.4: Effort Flow Diagram Node Nomenclature

NODES		
ENTITY	SYMBOL	DESCRIPTION
Component	1 - COMP.	COMP. = Component Name 1, 2, 3,… = Component Number
Functional Component	1 - FUNC. COMP.	FUNC COMP = Name of Function Provided by Feature of Parent Component 1, 2, 3,… = Number of Parent Component
Workpiece Object	WORKPIECE - OBJECT	WORKPIECE = External Object Operated on by the System OBJECT = Name of External Object

A Product utilizing relative motion functions can now be modeled in an effort flow diagram using this fundamental set of symbols. Products thus modeled can then be analyzed to identify areas where product evolution through component combination will have a high probability of success.

4.3.7 - Example of the Graphical Elements in Use

An example of a product modeled using an effort flow diagram with standard effort flow analysis symbols is shown in Figure 4.8. The model depicts the effort flow in a compact disc case during the four user operations: (1) opening the case, (2) closing the case, (3) removing the disc, and (4) replacing the disc.

There are three components in the system of interest. These components are numbered and labeled. Note the unique line style used to denote the compact disc; the compact disc is the object on which this product acts and is the work piece for this system.

The hands represent the external human inputs to the system. Looking at the input effort for the "open case" and "close case" operations, the top input is transmitted

through the external link to the "top half" component. The effort then flows from the "top half" to the "bottom half" via two distinct interfaces, one is the hinged interface and the other is the distributed interface along the edges of the case halves that provides the locking function in the closed position. Both of these interfaces are characterized as *general relative motion* links (R-Links). The effort flows for these two operations exit the product through the "lower half" component and its interface with the hand. Note the numeric designation on each of the external input links, and the directions of the arrows. The numeric labels indicate the operations for which the external inputs are active and the direction indicates the source and reaction relationship for the efforts.

For the "insert disk" and "remove disk" operations, the source of effort is the workpiece. Note the human effort is not modeled on the disk, as the disk is already outside the system boundary. The effort from the workpiece flows through the "insert" to the interface between the "insert" and the "bottom half." This interface is characterized as a *component relative motion* link (C-Link) for both operations. The interface is classified as a C-Link because as the disk is inserted or removed, the insert deforms. The deformation of the insert creates relative motion between the integral attachment fingers of the insert and the bottom half, but no relative motion occurs at the interface between the insert and the bottom half during the operation.

The lower human interface is active in each of the four operations; hence, the inclusion of all four operation numbers on that external link. In addition, the direction of the flow on the lower human interface is toward the hand, showing the role of the lower human interface as a reaction location or sink for the effort flows.

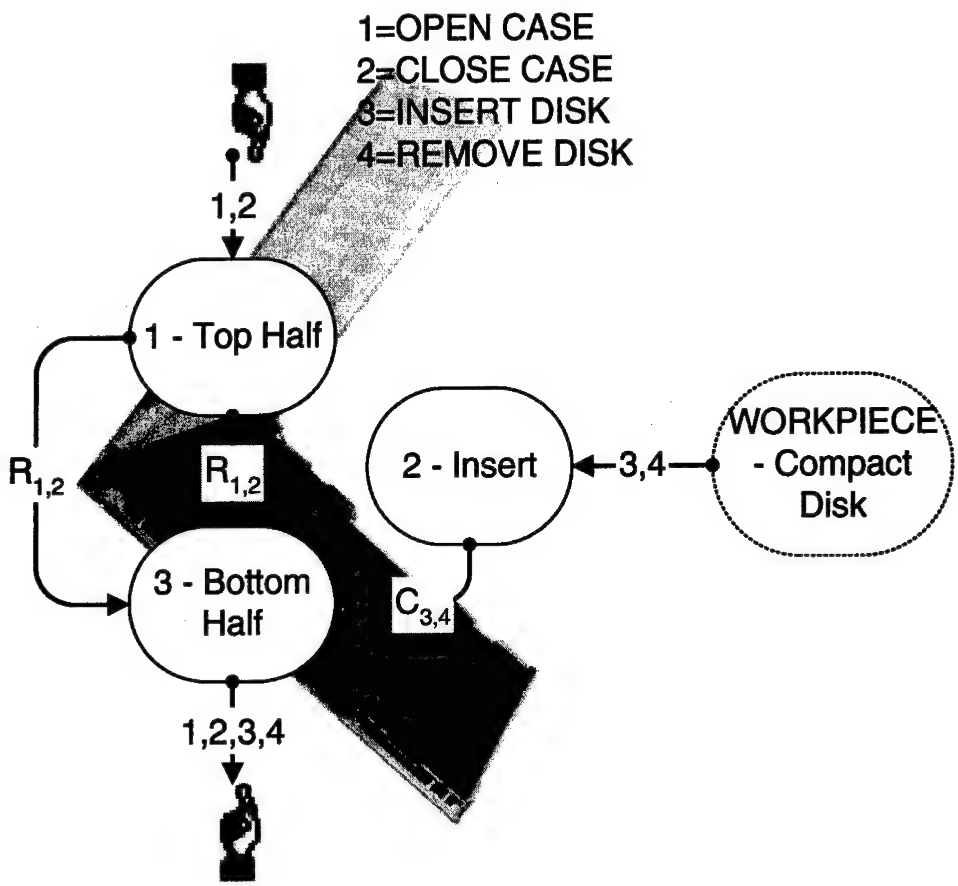


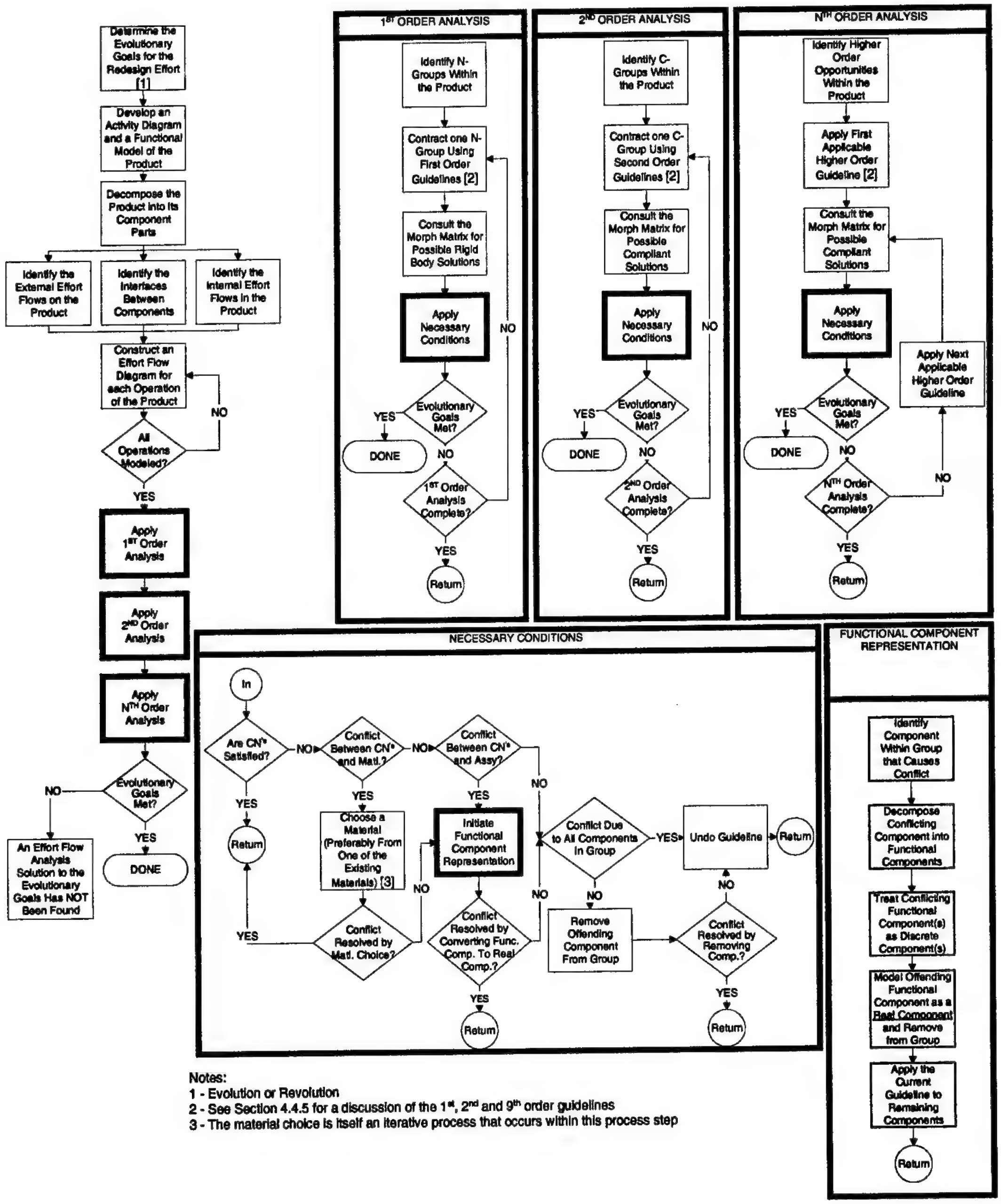
Figure 4.8: Example Effort Flow Diagram for a Compact Disc Case

From this example, it is apparent that there is a need for a systematic approach for the construction and use of the effort flow diagram. The next section presents the overall methodology of applying the effort flow analysis methodology, and the final section discuses some of the shortcomings that are identified for correction.

4.4 - Overview of the Effort Flow Analysis Process

Fundamentally, effort flow analysis is a systems modeling technique that enables directed product evolution. It provides an understanding of the interrelationships between parts by analyzing the structure of the system. As Bertrand Russell stated, "To exhibit the structure of an object is to mention its parts and the ways in which they are interrelated" [94]. Successful application of effort flow analysis to practical design

problems hinges on the systematic nature of the process. This section establishes the "steps" needed to apply effort flow analysis to general mechanical design problems. The steps in the effort flow analysis procedure are enumerated in the following paragraphs, while the overall structure of the procedure is shown in Figure 4.9.



Notes:
1 - Evolution or Revolution
2 - See Section 4.4.5 for a discussion of the 1st, 2nd and 9th order guidelines
3 - The material choice is itself an iterative process that occurs within this process step

Figure 4.9: Effort Flow Analysis Flow Chart

4.4.1 - Goal Evaluation

In any design effort, those responsible for directing the design progress, be it the designer, the product manager, the project leader, etc., must have a goal in mind. Some desired outcome must be established for a project to be undertaken in the first place. This goal is stated at one of two possible levels, evolution or revolution. The depth of effort flow analysis carried out is dictated by the redesign goal.

4.4.1.1 - Evolution

Evolution of a product implies making incremental evolutionary steps to improve the product. For example, evaluating fasteners for replacement with integral attachment features is an incremental evolutionary approach. Taking the evolutionary approach generally produces predictable outcomes that are the result of applying well-known design guidelines. The evolutionary goal seeks to direct the product along a smooth curve of product evolution through complexity reduction. There always exists the possibility that an effort to evolve a product will serendipitously produce a product revolution, but this would be an exceptional result and serendipity should never be counted on.

4.4.1.2 - Revolution

Revolution of a product implies a desire to create a dramatic change in the product, one that takes a leap along the evolutionary path, bypassing the incremental gains of stepwise evolution. The products that result from revolution are known as disruptive technologies [102] because of the effect they have on the competitive marketplace. To follow on the previous example, product revolution could be thought of as being analogous to going from using fasteners to creating a product that requires no assembly at all. The risk associated with a revolutionary product evolution goal is generally greater than for the stepwise evolutionary approach.

4.4.2 - Functional Modeling

Once the overall goals for a redesign effort are understood, the implementation phase of effort flow analysis can begin in earnest. The fist step in the effort flow analysis methodology is to apply the techniques of functional modeling [1, 49]. The first of those

steps is to establish the use patterns that are expected or observed in a product through the development of an activity diagram.

4.4.2.1 - Activity Diagram

An activity diagram is used to identify all the user operations associated with a product. This step may be made as simple or complex as needed depending on the number and complexity of the operating modes of the product. In addition, it should be understood that the user might be any entity who interacts with the product over the entire product life cycle.

At this point, a distinction must be made regarding the difference between user operations and product functions. User operations are the activities associated with the life cycle of a product. Activities are documented using an activity diagram as in Otto and Wood [1]. An operation is a user activity that initiates an effort flow at the system or sub-system boundary for the product of interest. In this context, an operation represents the *normal and expected* uses of the product, and may include those carried out by the end user, or they may be associated with: manufacturing, assembly, maintenance and repair, reuse, and recycling. The effort flow analysis method is indifferent to the type operation being addressed; therefore, it is not limited to a particular class of operations. The user operation in conjunction with the customer needs lead to the development of a function structure.

4.4.2.2 - Function Structure

Once the activities associated with the product are understood, it is possible to develop a functional model of the product. One possible representation of a functional model is a function structure [1, 49]. In contrast to the user operations, product functions represent the relationship between the input and the desired output of a product or its sub-systems. The product function is independent of any particular form of the product, and a sub-function is a component of the overall product function. Functions and sub-functions are described using the set of common basis functions first proposed by Stone and Wood [54, 98].

In effort flow analysis, it is critical that the overall functionality of the product be understood and documented because, ultimately, the product must maintain or improve in regard to overall functionality. Once overall operation and function of the product is understood and modeled, the physical relationships between components of the product must be established through decomposition.

4.4.3 - Product Decomposition

Once the product operations and the associated function structure are developed, the product is decomposed into its component parts. This decomposition can be accomplished by a number of methods. One approach is to physically disassemble the product, but this may not always be possible or even practical. For example, when applying effort flow analysis to a new product design, the only example of the product may be a digital model, in which case no physical example exists. In cases where physical disassembly is not adopted/feasible, it is possible to use an exploded view (digital or paper) of the product or a bill of materials to establish component naming.

The product is generally disassembled completely, but the level of disassembly may be determined by the level of analysis desired. For example, if a subassembly will remain intact during the redesign, then disassembly would not include the subassembly. That "untouchable" subassembly would then be treated as an individual component during subsequent analysis of the product. An example of a sub-assembly is an electric motor, which would not necessarily be considered for redesign along with the mechanism that it powers. In any case, each individual part of the product should be named and labeled with a number.

4.4.3.1 - Component Naming

Component naming should be done using a consistent naming convention, that naming convention may be internal to the company or one established by industry standards and practices, as discussed in section 4.3.1.1. An efficient means of capturing the interface information is in an adjacency matrix. In the adjacency matrix, the names or numbers for the components are used as the labels for the rows and columns.

4.4.3.2 - Internal Interface Identification

Identification of the component interfaces is carried out concurrently with product decomposition and component naming. The internal interfaces are identified as the locations where components have physical interaction. The nodes are connected via unlabeled and undirected lines at the interface locations. These lines simply represent the physical interface, and act as placeholders for the locations of the effort flow links that will be defined in the next section.

4.4.3.3 - External Interface Identification

The product is now completely disassembled and the components have been named and placed on the workspace to represent, as accurately as possible, the physical layout of the product. The next step is to establish the system boundary. The system boundary is determined by the extents of the product of interest. The extents may be the whole product, or some subassembly of the product. Establishing a clear system boundary is important in determining which components are considered eligible for component combination.

Once the system boundary is established, the locations of the external flows can be determined. The locations of the boundary crossings are the nodes where external effort links are placed. Determining the locations of external effort links is done by operation of the product. If operation is not possible, then simulation will be required. Simulation may be as simple as a mental visualization exercise or as complex as a 3-D solid model that is placed in a virtual operating environment. Physical prototypes are excellent tools for determining the external interfaces, and rapid prototyping provides one of the best short lead-time means of accomplishing the interface identification task.

4.4.3.4 - Adjacency Matrix

The final step in capturing the connectivity data for a product is to fill in the cells of the adjacency matrix. For the diagonal cells, enter the letter "E" if the component has any external interfaces and the letter "I" if the component has only internal interfaces. The off diagonal cells of the adjacency matrix are filled in with the connectivity data generated during identification of the internal interfaces.

The adjacency matrix is symmetric, and may be used as a full matrix or as upper or lower triangular. To accomplish the task of constructing the matrix, each component is analyzed to determine its interfaces with other components. Moving along a row, or down a column, a number one is entered for each component that interfaces with the component whose name heads the current row or column. If no interface exists between two components, the cell is left empty or the number zero is entered in the cell.

4.4.3.5 - External Flows

External interfaces are associated with two types of external effort flows (applied and resultant) for each operation of the product. The *applied* external effort flows are the efforts (forces, torques and moments) applied to the product to initiate or complete the desired operation. The *resultant* external effort flows are the efforts (forces, torques and moments) that result between the product and the environment because of the applied efforts. This is consistent with the principles of mechanics discussed in Chapter 3. The effort input to the product from the external flows leads to effort flow through the internal interfaces within the product.

4.4.3.6 - Characterization of Internal Flows

Once the external flows are identified and modeled, the internal effort flows can be characterized. The relative motion associated with each interface (effort flow path) can now be characterized using the four classes of relative motion links described in Table 4.1. Characterization of relative motion at the interfaces is one of the most important steps in the effort flow analysis methodology. Incorrect characterization at this early stage may lead to dead end paths later in the process when product evolution opportunities are erroneously identified based on incorrect assumptions about the nature of the interaction between two components. The quality of the overall model will depend on the fidelity with which this step is carried out, a cursory analysis can still provide insight, but the depth of that insight may be limited.

The issue that gives rise to incorrect characterizations is a paradox between the freedom to make modeling choices and the consequences of choosing poorly. In most modeling approaches, modelers have significant latitude in making assumptions and

choosing the level of detail that will be used. Characterizing relative motion interfaces in effort flow analysis is no exception, but the designer must be aware of the possible pitfalls of their modeling choices. Biases can creep into the modeling process, and these preconceptions may lead to the dead ends just mentioned.

At this point, the product is decomposed, the components are named, the interfaces are identified, and the relative motion is characterized. The next step is to bring these components together to construct an effort flow diagram for the product.

4.4.4 - Effort Flow Diagrams

The product-modeling phase follows the product decomposition phase. Product modeling begins with creation of an effort flow diagram to map the effort flow paths for each user operation. As alluded to in Chapter 3, an effort flow diagram is a semantic network of nodes and links that represent a collection of connected free-body diagrams. The free-body diagrams themselves are an abstract representation of the components of a product and the interaction between those components. At this point, free-body diagrams will be dropped as intermediaries, and the relationship between the nodes and components, and the links and interfaces will be discussed directly. The nodes of the effort flow diagram represent the individual components of a product. The links between the nodes represent the forces of interaction that occur at the interfaces between the components of a product. The direction of a link indicates the action/reaction relationship between the interfacing components, and is determined by the direction of effort flow as it passes from the external source through each of the affected components toward the external reaction. In addition to direction, each of the links has two labels, the first is the type of relative motion that exists between the nodes, and the second is the operation with which the characterization is associated. The four possible relative motion characterizations are: **N**, **C**, **R**, and **I** as derived previously and shown in Table 4.2, and the operations are determined using the activity diagram.

4.4.4.1 - Node Layout

One of the strengths of the effort flow diagram is its intuitive nature. Steps are taken in the development of effort flow analysis to strengthen its intuitive relationship

between the diagram and the product. One intuition building approach is to construct the effort flow diagram so the positions of the nodes reproduce as accurately as possible the positions of the components in the product. One way of achieving this goal is to construct the diagram using an exploded view, photograph, or other image of the product as a starting point. The approach taken in this work is to overlay the effort flow diagram on a digital image of the product.

Clearly, a three dimensional product cannot be completely reproduced in a two dimensional media such as a piece of paper or computer screen (3-D solid modeling not withstanding), but an attempt should be made to replicate the product layout as accurately as possible. It is proposed that several benefits are produced by mimicking the layout of the product in the layout of the effort flow diagram. The first benefit is that visualization of design changes is enhanced. Another benefit is that using the layout of the actual product in the effort flow diagram will strengthen the effort flow analysis intuition of the designer. Finally, diagram construction that mimics the product construction is expected to aid in error checking the placement of links by facilitating a more direct comparison between the modeled interfaces of the diagram and the physical interfaces of the product.

4.4.4.2 - Link Layout

After establishing the locations of the nodes in the diagram, the next step is to layout the links that connect the nodes to create a semantic network. The first step in laying out the links is to identify the external effort links. The external effort links are located on the external interface nodes. External interface nodes are those components that provide an energy flow path between the environment and the product. Identification of the external interface nodes is annotated in the adjacency matrix as an "E" on the diagonal associated with the component of interest. The external links are annotated with the operation number that corresponds with the operation that produces the effort flow at the external interface.

With the external flows laid out and annotated, the internal effort flows can be addressed. The internal flows are placed between nodes for each of the operations. Beginning with the node having the external interface, a link is placed between that node

and all subsequent nodes in the effort flow path for the current operation. Each link is then annotated with the relative motion characterization and operation number.

It is possible that there will be more than one interface between two components in a product. When separate and distinct interfaces occur, the diagram is constructed using two separate effort links between the component nodes. This multi-path information more accurately represents the physical configuration of the product, and is important for use during the rest of the effort flow analysis process.

4.4.4.3 - Loop Back through all User Operations

If the discrete approach to effort flow diagram construction is used, the diagram is complete when all the links have been placed for a single operation. At which point, the next diagram can be constructed by applying the node layout and link layout steps again. If the aggregate approach is used, then the link layout step is repeated on the aggregate diagram for the remaining user operations. As each operation is modeled, additional links are added and characterized until the use pattern of the product is fully represent.

4.4.4.4 - Identify Relative Motion Groups

Once the effort flow diagram is fully constructed, the business of identifying product evolution opportunities can commence. The easiest approach to identifying opportunities is to look for groups of components connected by a single type of link. For example, several components connected by N-Links or C-Links. Other more complex structures are possible as well, but the foundation of effort flow analysis is in the identification of single link type groups. Identification of these groups is the focus of the basic methodology and allows application of the product evolution design guidelines that follow.

4.4.5 - Product Evolution Design Guidelines

The product evolution guidelines for effort flow analysis evolved throughout the development of the methodology, beginning as far back as the force flow propositions from Chapter 2. The guidelines presented in this section represent the fundamental guidelines for the method. These guidelines use a classification scheme that is based on

the relative motion characterizations, i.e. the link type [47, 103]. The design guidelines are ordered hierarchically, beginning with the guideline that has the highest likelihood of achieving a successful component combination. The guideline hierarchy is stated as the order of the guideline (1^{st}, 2^{nd}, and N^{th}). The higher the order of the guideline, the lower the likelihood of success. The rationale for ranking each guideline is discussed in the guideline support sections.

The process for applying the design guidelines is a feedback loop, where a guideline is applied, and the design concept that results is evaluated against the necessary conditions for component combination. If the design concept satisfies the necessary conditions, then the next guideline is applied to the now evolved product. If the necessary conditions are not satisfied due to a conflict between the customer needs and the design concept, then the reason for that failure is determined. The next guideline is not applied until the necessary conditions have been satisfied, or the conflict is found to be irreconcilable, in which case the product is reverted back to the previous state.

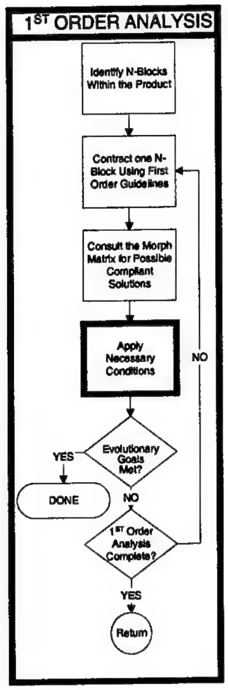


Figure 4.10: 1st Order Analysis Module

4.4.5.1 - 1st Order Analysis – The Non-Relative Motion Link: "N-Link" (O^1)

Groups of components connected by N-Links are 1st-order candidates for combination, and the logical flow of 1st order analysis is shown in Figure 4.10. This product evolution guideline represents the legacy of force flow analysis where the premise is the grouping of parts between which no relative motion exists. These types of interactions represent the simplest opportunities for component combination. Combining components grouped in this manner satisfies the three DFA component combination criteria of Boothroyd *et al.[6]* discussed earlier.

N-Link Guideline:

If the interaction between two components can be represented by a N-Link, it may be possible to combine those components directly. N-Linked components typically provide the following functions: transmit effort, allow DOF for assembly, and material-based functions such as resist loads, or transfer heat. Combination is contingent upon the satisfaction of the material and

assembly/disassembly functions. Assuming these are satisfied, the primary function for the combined N-Link components is to transmit force or torque.

Once the guideline is applied, the "Necessary Conditions" module is activated to determine the feasibility of the design concept that results from applying the guideline. After the "Necessary Conditions" are satisfied, the results are compared to the evolutionary goals, and a decision is made about further iteration. If the goals are met, then the process is complete, and the "End Game" has been reached. If the goals are not met, then the 1st order analysis is continued until no N-Link groups remain to be combined. Once no further groups exist, control of the process goes back to the overall methodology.

Guideline Support: Groups of components connected by N-Links are classified as first-order because they represent one of the fundamental tenets of the DFMA approach to component combination presented by Boothroyd and Dewhurst [6]. The DFMA approach is also espoused by many noted authors in the field of mechanical design theory [1] [12], [104], [25], [63], [1]. Application of the N-Link guideline provides the strongest likelihood of success with the least impact on product function and mechanical properties. Hence, the N-Link guideline is applied first before further effort flow analysis is carried out.

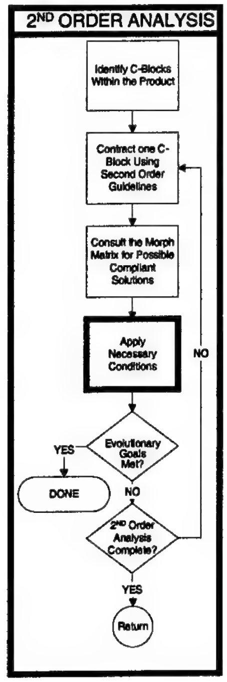


Figure 4.11: 2nd Order Analysis Module

4.4.5.2 - 2nd Order Analysis – The Component Relative Motion Link: "C-Link" (O^2)

Groups of components connected by C-Links are 2nd-order candidates for combination, and the logical flow of 2nd-order analysis is shown in Figure 4.11. A C-Link implies deformation of one or more components as force is transmitted. C-Links may represent either elastic or plastic behavior in the interfacing components. For example, components that experience single or multi-cycle plastic deformations are represented by a C-Link.

C-Link Guideline:

If the interaction between two components can be represented by a C-Link, it may be possible to combine those components directly into a compliant mechanism by making parametric changes to the geometry of the components involved. C-Linked components typically provide the following functions: transmit force, store/supply energy, allow DOF, and material based functions such as secure solid and inhibit energy flow.

Combination is contingent upon satisfaction of the material and assembly/disassembly functions, as well as functional relationships to include the necessary deformation and/or energy storage properties provided in the original product design. Assuming these are satisfied, the primary performance functions for the combined C-Link component are to allow DOF, transmit force, and store energy.

Once the guideline is applied, the "Necessary Conditions" are satisfied just as they were for 1st-order analysis.

Guideline Support: Groups of components connected by C-Links are classified as 2nd-order candidates because they represent a reduced likelihood for successful component combination when compared to the more fundamental approach of the N-Link guideline. The presence of a C-Link implies that an intended relative motion function(s) exists in the original components. Component combination has the potential to impact these deformation based product function(s), and hence the likelihood of producing a successful combination using compliant components is high, as compliance is used in the original design. However, satisfaction of the three necessary functional conditions is typically more difficult to ensure simply due to the presence of relative motion.

The creation of a compliant mechanism from two parts connected by a C-Link requires the material and/or geometry of the combined part to have properties that provide the deformation/return functions originally performed by the separate deformable part while providing the support functions of the interfacing support component. In addition to the deformation requirement, the material used in the combined component must have specific material properties related to other functional requirements such as color, creep resistance, conductivity, weight, etc required in the original design. The greater the number of functional requirements, the greater the material selection challenges become.

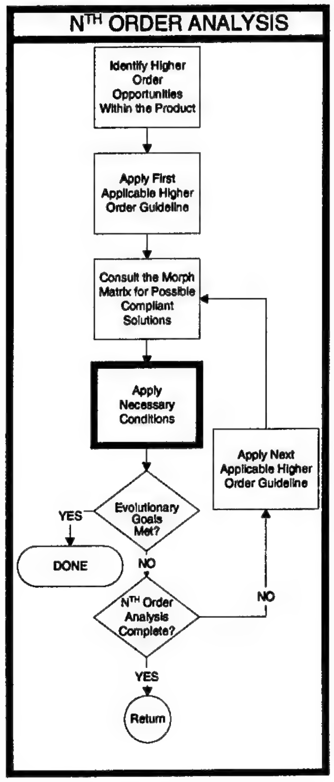


Figure 4.12: Nth Order Analysis Module

4.4.5.3 - Nth Order Analysis – The Relative Motion Link: "R-Link"(O^{N}, Nth Order)

Groups of components connected by R-Links are Nth-order, candidates for combination, and the logical flow of Nth order analysis is shown in Figure 4.12 In the original guidelines for effort flow analysis [22, 103], R-Links are designated as "combinable" only through significant redesign effort. This hypothesis is modified here to reflect the fact that the level of effort required to achieve component combination across certain R-Links is not as significant as originally implied. R-Links take many forms to include: kinematic joints of all kinds, sliding contact in slots and guides, gears, and bearings. R-Links may also represent the interface between a compliant member and a support member if that interface is not fixed.

R-Link Guideline:

> If the interaction between two components can be represented by a R-Link, it may be possible to combine those components directly into a compliant mechanism provided the original relative motion function can be provided through deformation of the combined components. R-Linked components typically provide the following functions: allow DOF and transmit force and the primary material based function is to regulate mechanical energy.
>
> Combination is contingent upon satisfaction of the material and assembly/disassembly functions, as well as functional relationships to include the necessary path generation and end point positioning properties provided in the original product design. Assuming these are satisfied, the primary performance functions for the combined R-Link component is to allow DOF and to transmit force.
>
> A first cut at synthesis of the combined component is to fuse the components into a compliant mechanism having the original material and geometry, then make parametric changes to refine the combination.

Once the guideline is applied, the "Necessary Conditions" module is activated to determine the feasibility of the design concept that results from applying the guideline. After the "Necessary Conditions" are satisfied, the results are compared to the evolutionary goals and a decision is made about further iteration. If the goals are met, then the process is complete, and the "End Game" has been reached. If the goals are not met then the N^{th}-order analysis is continued until no further N^{th}-order guidelines are available for application. Once no further guidelines are available, control of the process goes back to the overall process and the "End Game" decision is made.

Guideline Support: Groups of components connected by R-Links are classified as N^{th}-order, ($N = 3$ or higher), candidates because they represent the least likelihood for successful component combination when compared to the N-Link and C-Link combinations. The solid mechanics criteria discussed above give the defining guidance on component combination across R-Links. These criteria may be difficult to satisfy as the magnitude or spatial displacement of the relative motion increases.

4.4.6 - Necessary Conditions for Successful Component Combination

Implicit in the effort flow analysis methodology of Figure 4.9 is the assumption that the redesign of a product or subsystem will either maintain or improve functionality while also improving some other performance aspect of the product such as cost or reliability. With this goal in mind, any design variant of the original product must

provide the original product functions; hence, the necessary conditions for a successful redesign are based on function. It is proposed that three fundamental functional criteria form a set of necessary conditions for component combination in the mechanical energy domain. The three necessary functional conditions are given as follows:

<u>Degree-of-Freedom Condition</u>: *The original degree-of-freedom based functions must be maintained in the resulting combined component, rigid or compliant.*

<u>Energy Transmission Condition</u>: *The material of the combined component must satisfy the energy transmission functions required for the product.*

<u>Actuation Force Condition</u>: *The actuation force of the resulting rigid or compliant mechanism must be within reasonable and achievable bounds for the actuating component.*

These three functional conditions represent necessary conditions for component combination, i.e. they represent the minimum requirements necessary for a successful component combination. These conditions do not meet sufficiency requirements, as they do not capture the full spectrum of possible functional requirements that must be satisfied for a component combination to be successful, i.e. meeting the three functional conditions is insufficient to guarantee a successful component combination. In addition to the functional criteria, fundamental physical laws must also be satisfied. It is proposed that these three functional conditions map to three solid mechanics laws to form a system of relationships that must be satisfied.

4.4.6.1 - Solid Mechanics Conditions

The three solid-mechanics based laws are given as follows:

Strain-Displacement Law,

Stress-Strain Law (Material Constitutive Relationship),

Equations of Equilibrium (Force or Stress).

These three laws are inviolable in all cases, and completely define the material state in the product. They are intrinsic to the physics of mechanical efforts. The relationship between the physical laws and the functional conditions is best described as a system of coupled relationships.

The degrees-of-freedom condition is based on the premise that if motion is provided in the original components, the motion-based function of those components must be preserved in the redesigned component. For mechanisms, the motion has two fundamental requirements, the first is path generation, and the second is end-point positioning [83]. The equilibrium and the strain-displacement (especially for compliant mechanisms) laws are critical in satisfying this condition.

The energy transmission condition is based on the concept of *energy flow* from functional modeling [1, 49, 52]. In the static or quasi-static mechanical energy domain model used in effort flow analysis, *energy flow* is represented either by forces or by torques. Based on this model, efforts will flow through the material of the combined components derived from effort flow analysis, and the material strength of these combined components must be sufficient to provide the "transmit energy" function. This strength criterion necessitates invocation and satisfaction of the stress-strain law.

The actuation force condition is a bounding relationship where the force has a minimum for sensitivity reasons and a maximum for achievability reasons. Equilibrium and strain displacement laws are again critical.

The criteria for successful component combination just discussed are developed specifically for the application of effort flow analysis to the synthesis of compliant mechanisms as a means of product evolution. The inability to satisfy one or more of the necessary conditions leads to a design conflict. Resolution of design conflicts is an integral part of the effort flow analysis methodology, and is discussed in the next several sections.

4.4.6.2 - Conflict Resolution

After each guideline is applied, the resulting design variant must be checked for conflicts against the necessary conditions. To check for conflicts, the effort flow analysis methodology of Figure 4.9 contains a "Necessary Conditions" module with multiple decision points. The decision points are related to conflicts that arise between the functional and material conditions and the customer needs (CN's). This is an area of the methodology where functional modeling and customer needs analysis come into play, as

conflict identification requires that the designer deduce the sub-functions and customer needs that are affected by each guideline that is applied.

The Necessary Conditions Module from the effort flow analysis process diagram is shown in Figure 4.13. Following the flow of the module, if the design variant that results from a guideline satisfies the customer needs, then no conflicts are identified and the guideline process continues. If a conflict does arise, then its cause must be determined, and a resolution developed. Three fundamental types of conflict exist, material conflicts, assembly conflicts, and isolated component conflicts. The next three sections will discuss these types of conflict.

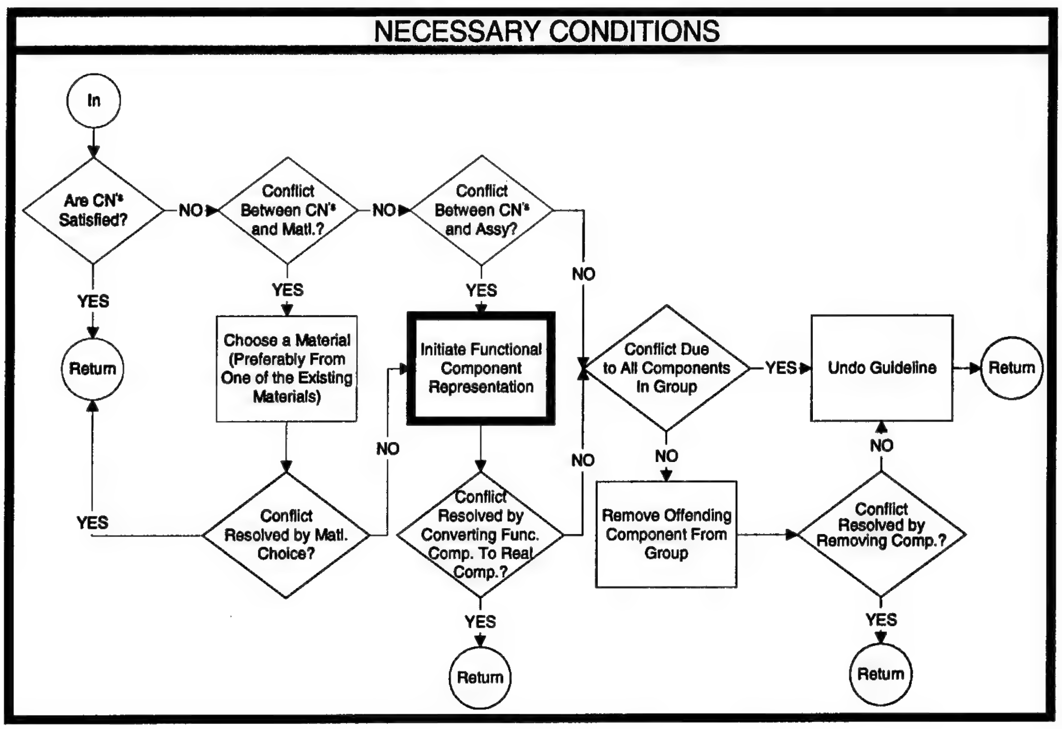


Figure 4.13: Necessary Conditions Module

4.4.6.3 - Material Conflicts

The first test for a potential conflict in the "Necessary Conditions" module of Figure 4.13 is between the CN's and the materials used in the design concept. If the conflict is not material related, then a check for an assembly conflict is initiated. If the

conflict is materials related, then a search for a suitable material is initiated. The process of material selection is nontrivial, and a full treatment of this topic is beyond the scope of this dissertation. Several excellent references such as Ashby [105] and Dieter [104] exist for the material selection process, and other material selection resources such as industry or company specific data and archives are possibilities as well. One of the most likely material related conflicts occurs when components made of different materials are identified as candidates for combination. In this case, the preferred choice is to use one of the materials from the candidate components to satisfy the necessary conditions. In any case, once a material choice is made, the process continues by checking the design concept against the necessary conditions for the chosen material.

If the chosen material resolves the conflicts, then the overall process for the guideline continues. If a material conflict remains, then the next step is to use the "Functional Component Representation Module." The "Functional Component Representation Module" is designed to isolate the region of the component that is the source of the conflict. If the conflict is material related, but cannot be solved by choosing a single material for the combined component, then the possibility exists that there is a function sharing conflict to be resolved.

4.4.6.4 - Assembly Conflicts

The second conflict addressed in the "Necessary Conditions" module of Figure 4.13 is conflict in the assemblability of the design concept. If the customer needs are not satisfied, and the conflict is not materials related, then the next possibility is that an assembly conflict exists. A check of the design variant for assembly conflicts leads to two possible outcomes. The first is that the conflict is not related to assemblability, and the "Necessary Conditions" process will continue to the next step. If, on the other hand, the conflict is assemblability related then the next step is to decompose the design variant using the functional component representation.

4.4.6.5 - Functional Component Representation

Both material and assembly conflicts can arise due to function sharing in a component. Function sharing conflicts occur when a component identified for

combination performs more than one function, and one or more of those functions are in conflict with the functions of the other components identified for combination. One way to gain insight into the multi-function nature of a component is by using the functional component representation described earlier in this chapter.

The first step in resolving functional conflicts as shown in Figure 4.14 is to identify the component in the group that is the source of the conflict. The offending component is then decomposed into separate "Functional Components." Functional components represent the regions, features, and interfaces of a function-sharing component that are directly attributable to providing a particular function. The goal is to isolate the region of the original component that is the source of the conflict and treat it as a separate component. This "virtual" component is then treated as if it were a separate and distinct component within the product system.

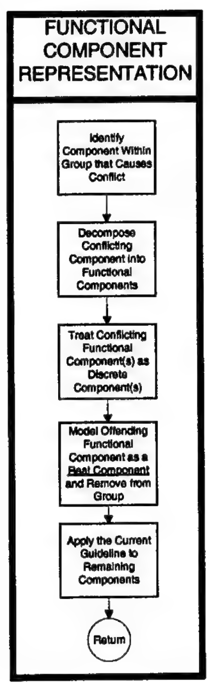


Figure 4.14: Functional Component Representation Module

The interfaces that previously existed between the original multifunctional component and neighboring components are transferred to the corresponding functional

component. In addition, new links are placed between the functional components to represent the interactions between regions of the original component.

Now that the function sharing has been decomposed and the offending component has been isolated, it may then be possible to apply the current design guideline by excluding the conflicting functional component and manipulating the remaining functional components along with the other components in the group to achieve a successful component combination. The result is a sub-optimal solution that does not achieve the total evolution goal for the identified group of components, but does make an incremental advance.

4.4.6.6 - Isolated Component Conflict

The third and final conflict addressed in the "Necessary Conditions" module is that of an "isolated" component causing a conflict. In this case, an "isolated" component is a single component or a subset of components in the candidate group that is the source of conflict. If all the components in the group are in conflict, then no further options are available and the guideline is undone. Otherwise, an isolated component may be the source of conflict and the offending component is addressed. The isolated component is removed from the candidate group, and the current guideline is then applied to the remaining components in the group. If the customer needs can be satisfied, then the process for the current guideline continues to the next step. When the original group has only two components, then the effect of this step is to undo the current guideline.

4.4.6.7 - Unresolved Conflicts (Irreconcilable Differences)

The final check in the "Necessary Conditions" module is whether the removal of the isolated component has solved the conflict; the module has run its course and the next step in the current guideline is carried out. If the conflict has not been solved, then all avenues have been exhausted and the current guideline is infeasible for the current product and must be undone. Undoing the guideline returns the product to the configuration that existed prior to applying the current guideline.

4.4.7 - "End Game"

The effort flow analysis process continues until one of two possible exit criteria are satisfied. The exit criteria are determined from an assessment of the relative success of the overall redesign effort. The first criterion is satisfied when the evolutionary goals are met. The goals may be met at any of the guideline levels shown in Figure 4.10, Figure 4.11, and Figure 4.12 or at the end of the overall process shown in Figure 4.15.

The second criterion is satisfied when the evolutionary goals cannot be met. If the evolutionary goals of the design effort are not yet achieved, but all the available guidelines have been attempted, then effort flow analysis has run its course for the product under consideration. At this point, all the options have been expended and the product has been evolved to the extent possible using the guidelines available in the effort flow analysis methodology, this exit state is also shown in Figure 4.15.

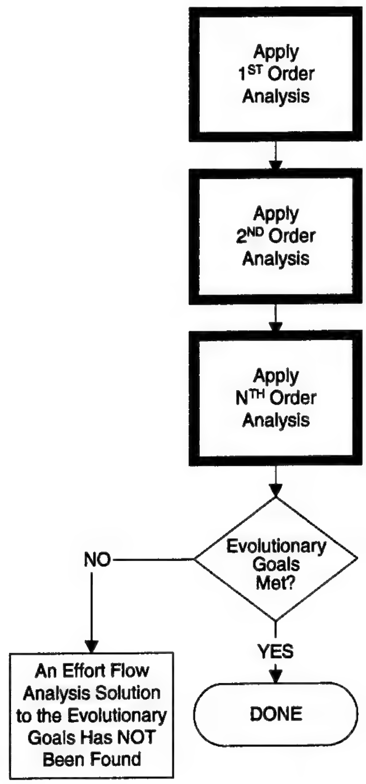


Figure 4.15: "End Game" section of Overall Effort Flow Analysis Process

4.5 - LATENT SHORT COMINGS OF THE METHOD

After applying the effort flow analysis methodology to several products as a redesign exercise, questions arise about the breadth of the fundamental design guidelines presented in this chapter. There is little question that the guidelines form a suitable foundation, whether they are robust enough to address issues that arise in practical applications from the domain of mechanical effort transmitters remains as an issue.

The first question is, "Is the method able to treat issues associated with links that are active for multiple operations?" It seems especially important that the guidelines be able to give guidance on how to proceed with these multi-operation links, especially when more than one relative motion characterization is present on a link.

Another question arises as products evolve, "How do we proceed with a product that is significantly evolved?" In an evolved product, the evolution opportunities that

remain must come from graph structures that can only be classified as N^{th}-order opportunities, but the foundational guidelines at this point in the development of effort flow analysis only address R-Links. Examples of higher order opportunities may include parallel and serial links and other graph structure related forms in the effort flow diagram that may be markers of product evolution opportunities.

Additionally, "Has development of the methodology met the goal of developing a systematic approach to synthesizing compliant mechanisms?" One of the goals of effort flow analysis from the beginning is to develop a systematic approach to synthesizing compliant mechanisms that moves beyond the traditional component combination techniques embodied in the DFMA guidelines of Boothroyd *et al* [6]. This goal has not yet been met, as the foundational guidelines are not yet at that level.

Finally, the question "How can the knowledge base contained in the results of *ad hoc* product evolution as it is practiced in industry be captured?" must be answered. More insight is needed in the guidelines regarding how product evolution using rigid and compliant mechanisms is accomplished in industry. It is believed that much can be learned by answering this key question.

These issues taken in concert provide the motivation for the next step in the research effort, which is to more fully develop the effort flow analysis guidelines. The three foundational guidelines presented in this chapter are valid, and they are applicable to a wide swath of mechanical effort transmitters, but they do not cover the depth and breadth of product evolution opportunities that are available. To answer the questions just posed, an empirical study is proposed to investigate making the effort flow analysis methodology more robust through the development of a larger set of design guidelines.

Chapter 5 - Empirical Study

5.1 - INTRODUCTION

At the end of the last chapter, four questions arose from apparent shortcomings in effort flow analysis. The questions are restated here:

> "Is the method able to treat issues associated with links that are active for multiple operations?"
>
> "How do we proceed with a product that is significantly evolved?"
>
> "Has development of the methodology met the goal of developing a systematic approach to synthesizing compliant mechanisms?"
>
> "How can the knowledge base contained in the results of *ad hoc* product evolution as it is practiced in industry be captured?"

These four questions provide the motivation for the current chapter, where the three foundational effort flow analysis guidelines are expanded using an empirical product study. The foundational guidelines will be tested for validity, and new guidelines will be added to the toolbox of effort flow analysis that expand the applicability of the method to a wider scope within the mechanical domain.

The goal of the chapter is achieved by first establishing the mechanism used to capture the knowledge needed for effort flow analysis to address the questions above as well as others to come. The knowledge capture mechanism of effort flow analysis is a form of product evolution design guideline. The source of the guidelines is then defined by an empirical study and the methodology used to conduct the study. The overall process followed in the study is treated, as are the desired outcomes and data collection metrics. To demonstrate the study approach, one full product study case is presented along with the guidelines that ultimately evolved from that study. As with any study, the question of validity of the results must be addressed, hence an analysis of the validity of the results is presented. Once the validity of the approach is established, the fruit born of the study is presented in the form of a sorted table of effort flow analysis product design and evolution guidelines.

5.2 - GUIDELINE THEORY

Design guidelines are the embodiment of the captured knowledge in a heuristics based design methodology such as effort flow analysis. Guidelines provide a means to store and reuse design knowledge with the potential to be effective at any stage of design. According to Roozenburg and Eekels [106], design rules can be either algorithmic or heuristic. "Any design rule that cannot be converted into an algorithm is heuristic." Algorithmic rules are based on a well-known relationship between cause and effect, as in physical laws, and they produce predictable and reliable results. Heuristic rules are based on weak knowledge where the relationship between cause and effect is less well defined and they are not guaranteed to produce the desired solution, but they are successful often enough to be useful. The effort flow analysis design guidelines are best classified as heuristic, because they are based on observation of existing products and they have an underlying basis in physical laws. Each guideline is known to have at least one successful implementation, but none of the guidelines implies a global guarantee of success. The fact that a guideline does not work in all cases does not discount its value in design. As long as the guideline produces the desired results in the types of artifacts for which it is appropriate, then its value as a piece of captured artifact design knowledge is tangible.

The design guidelines developed for effort flow analysis are collected using a process modeled after one proposed by Nowack [107]. In this process, guideline collection is viewed as a knowledge acquisition task. Debenham [108] stated, "The goal of the knowledge acquisition phase is to construct a complete, consistent, correct and non-redundant model of the application which is comprehensible to the domain expert and which is in a sufficiently precise form to enable a trained person to translate it unambiguously into some implementable formalism." In addition, Debenham noted three requirements for collected knowledge. (1) The terminology must be unambiguous. (2) The basic elements of the knowledge must be identified and classified. (3) The element of knowledge must have, at most, a single functional association and must be expressible as a statement in the application model.

5.2.1 - Guideline Formalism

The form of guideline used in effort flow analysis is based on guideline research from various fields. The most notable sources of guideline research are medical practice, [109-112], design science, [3, 10, 49, 113-116], and human factors engineering [117]. The guidelines take two general forms: conditional recommendations and imperative recommendations. Conditional recommendations are rules of the form:

If CONDITION then ACTION(s) {because REASON(s)}

A condition is specified by one or more combinations of a decision variable such as the link type or graph structure e.g. N-Link group, serial links, parallel links, etc. Fulfillment of the condition initiates at least one guideline-specified *action,* while the *Reason* elements explain why the action has been initiated.

Imperative recommendations are broadly applicable directives (which parallel the actions in a conditional recommendation), e.g.,

> Large deformations generally require more than parametric changes to the geometry to achieve satisfactory component combination results.

Imperatives often include terms such as "require," "must," and "should" but do not contain conditional text (e.g., "if," "when," "whenever") that would limit their applicability to specified circumstances [111]. With the exception of condition elements (which exist only in the conditional guidelines), the elements of the guideline structure are similar for both imperative and conditional guidelines. Each guideline represents a sub-process within the overall effort flow analysis methodology. The form used to record the guidelines in effort flow analysis is loosely based on the GuideLine Interchange Format (GLIF) developed by the Intermed Collaboratory [118]. The result is a guideline format that is based on accepted practice from both medical research and from design science.

5.2.2 - Guideline Template

Using the fundamental guideline form just discussed, a guideline template is formed that satisfies the needs of effort flow analysis. The template is shown in Table 5.1, where each entry of the table describes the contents for that cell in the actual

guideline. Note that some of the entries are optional, as these aspects of the guideline may not be applicable in every guideline.

Table 5.1: Effort Flow Analysis Design Guideline Template

GUIDELINE NAME	
Recommendation	The *Recommendation* is a conditional or imperative statement that forms the foundations for the guideline
Guideline steps	The *Guideline steps* contain information about the relationships between steps in a recommendation, which is stored in an *algorithmic* form that shows the process flow of the guideline.
Branch steps	The *Branch steps* describe optional conditions or actions that relate to a particular rule and are often recognizable by the presence of "or" statements in the recommendation text. Branch steps often invoke another guideline, e.g. the application of distributed compliance or localized compliance approaches to compliant mechanism synthesis. Finally, the *synchronization steps* provide the linkage between the current guideline and subsequent or parallel guidelines that may be applicable.
Conditional steps	The *Conditional steps* are the criteria for a successful application of the guideline; these are usually, but not always, the necessary conditions. **(Optional)**
Criterion	The *Criterion* define the specific conditions under which the guideline may or may not be applicable. **(Optional)**
Supplemental material	The *Supplemental materials* are solution representations or morphologies. These materials are the previously observed or expected solutions for this particular guideline. The solutions may take the form of photos or drawings of observed solutions, or may be in the form of graph structures that model those solutions.
References	The *References* section contains citations to specific sources that support a particular guideline. The presence of a citation highlights the fact that not all the guidelines result from this study; some guidelines are taken from the literature, and formatted to conform to the guideline format used in effort flow analysis. **(Optional)**
Guideline Support	The *Guideline support* that led to a particular effort flow analysis recommendation is noted. The strength of evidence is ranked using a 4-star rating system

5.2.3 - Strength of Empirical Support Rating System

Of the entries in the guideline template, the *Guideline support* entry requires further discussion. The guideline support entry represents an assessment of the strength of empirical evidence for each particular guideline, which is measured based on the number of times a guideline is observed in the evolution of an original product. The approach taken is to calculate the mean, standard deviation, and confidence interval for each guideline measured over all 33 of the evolved products. Implicit in this approach is an assumption that the frequency of application for a particular guideline is normally distributed over the relatively small population of products observed.

1. The mean frequency of application is calculated for each guideline, $\bar{f}_g$.
2. The standard deviation is calculated, σ.
3. Using the mean and standard deviation, a confidence interval is calculated using a 95% confidence factor.
4. Using the frequency of occurrence as the first sort parameter, and the confidence interval as the second, the guidelines are ordered from most frequently observed to the least frequently observed.
5. Guidelines with $\bar{f}_g \geq 75\%$ are assigned four stars,
6. Guidelines with $50\% \leq \bar{f}_g \leq 75\%$ are assigned three stars,
7. Guidelines with $25\% \leq \bar{f}_g \leq 50\%$ are assigned two stars,
8. Guidelines with $\bar{f}_g \leq 25\%$ are assigned one star.

The rating system is developed to reflect the relative contribution of empirical data versus expert judgment in the development of the guideline. It should not be inferred that a guideline with four stars is "better" or more valid than a guideline with one star--it simply has more support that is empirical. Furthermore, the relative importance of any particular guideline depends on the design situation and the evolutionary goals for the design effort.

Table 5.2: The 4-Star Rating System (Adopted from [117])

****	Empirical data forms the greatest proportion of the support used to develop this design guideline. Little expert judgment is required to develop this design guideline.
***	Empirical data from a majority of the products was used to develop this design guideline. Expert judgment is used, mostly as support, to develop this design guideline.
**	Based on limited empirical data; research findings may not all agree. Expert judgment is primarily used to develop this design guideline, although the empirical sources were used as secondary sources.
*	Little or no empirical data used to develop this design guideline. Based primarily on expert judgment or design convention.

5.3 - EMPIRICAL STUDY –METHODOLOGY

A significant portion of this dissertation is related to or dependent upon the completion of the empirical product study. The product study is proposed as a tool for assimilating design knowledge that will then be used to develop design guidelines that support effort flow analysis as a product evolution methodology. The study seeks a set of products that use relative motion functions as determined using the set of common basis functions [54]. The study samples are selected from the durable and disposable goods product domains. Durable goods are defined to be products with an expected life of one year or more, and include goods such as furniture, autos and TVs. Disposable goods are, by exception, those products that are not durable.

5.3.1 - Assumptions

Several assumptions are needed in completing this study. The first is that a finite set of guidelines exists and that set is sufficient to implement the effort flow analysis method. The first characteristic required for membership in the set of guidelines that implement effort flow analysis is that a guideline is to be stated in the form of a recommendation. Recommendations are the unique components that distinguish guidelines from other publications; recommendations are intended to influence practitioners' behavior. When recommendations are analyzed into atomic concepts (and perhaps encoded in a structured vocabulary), they can be executed by formal logic [111]. Recommendations can be categorized as *conditional* or *imperative* statements.

Conditional statements clearly delineate the situations in which they apply, while imperatives are broadly applicable to the target population and do not impose constraints on their applicability. The second characteristic required for membership in the set of guidelines that implement effort flow analysis is that the guideline addresses an issue and recommends an action in the reference frame of the effort flow diagram. In other words, the guideline must treat issues relating to or arising from the links and nodes of the diagram. A caveat regarding these restrictions on membership must be made, for it is certain that very compelling guidelines will become apparent during the course of the investigation that require exceptions to these restrictions for various reasons.

A second assumption is that the number of products investigated in the study is a sufficiently large population to guarantee with reasonable certainty that the set of guidelines that is sought has indeed been found. To test this assumption, the number of guidelines collected for each product group is tallied and that number of guidelines will be plotted against the number of products studied. The goal is to reach a horizontal asymptote that shows that no new guidelines are gathered with the inclusion of a new product in the study. Further support of this assumption comes from the fact that every product in the study includes components that provide the relative motion functions determined from the outset to be necessary for inclusion of a product in the study.

A final assumption is that insights about product evolution can be gathered from groups of products that all provide the same functions, but are not all produced by the same manufacturer. This assumption is made because the function set that describes each product in a group is the same, i.e., each product has the same functional model. It is also assumed that given the "original" product and the various design environments that exist in the companies that produce the "evolved" products; that each of the "evolved" products would have been produced by the original producer had they been free to pursue such evolution in the design environments of the other companies. Constraints that could prevent a producer from pursuing product evolution include sunk costs in tooling and machinery that limit the scope of design changes over time, a corporate culture that prefers stability over innovation, or a target market that prefers for example a "retro" style product that is purposely left in its original state.

5.4 - Empirical Study Overview

The first step taken in the study is to select a set of representative products. In selecting products, particular attention is paid to choosing products that demonstrate evolutionary progress in the form of a before-and-after example. After the set of product examples have been selected, they are decomposed and analyzed. Decomposition and analysis is carried out using the effort flow analysis methodology, which is applied to current and previous versions of the products. Observations are made about the evolution of the product and how that evolution can be systematized in the effort flow analysis methodology. In the end, the collected observations from the study will be formalized using a structure for design guidelines developed from several guideline formulations. The following sections describe the purpose, hypothesis, metrics, and procedure that form the basis for the empirical study.

5.4.1 - Purpose

The purpose of the study is to identify and extract design guidelines and design morphologies associated with compliant solutions used in the design of existing products. The goal is to use the guidelines and morphologies to develop a systematic method for compliant mechanism design that is integral to effort flow analysis.

5.4.2 - Hypothesis

The hypothesis for this study relates to the existence of common and recurring graph structures in effort flow diagrams. The hypothesis states "A set of common component combination graph structures exist across different product domains and product scales for each of the feasible relative motion classes." These common graph structures are expected to lead to insights regarding design guidelines and design morphologies that led to the use of compliance in current products. Studying these current products and the implied design guidelines that led to the creation of compliant solutions will lead to a database of captured knowledge in the area of compliant mechanism design.

5.4.3 - Metrics

In order to prove or disprove the hypothesis just stated, there must be a measurable aspect to the study. In light of this fact, several metrics have been identified for collection. A list of the metrics collected for the study is presented in Table 5.3, and the value of each metric in supporting the hypothesis is stated in the following discussion.

5.4.3.1 - Functions

The number of functions associated with each product is determined using functional modeling [1, 49]. The functions of the product are then associated with the components of the product to develop a component-function matrix. The component-function matrix is similar in nature to a product-function matrix [56, 119] where a product vector is created that contains each of the functions and sub-functions of a product, that product vector is then aggregated into a matrix representing the functional content of many products. The result is stored knowledge about the functional content for a large set of products used to aid design synthesis and product architecture efforts. In the case of the component-function matrix, the result is a matrix of the components associated with each of the functions of the product [120]. The benefit of this approach is the insight that is gained into which components provide which functions in the product, as well as insight into the degree of function sharing in the product before and after evolution. A higher degree of function sharing is generally regarded as an evolution of the product. This view is alluded to in the drive toward manufacturing cost reduction through component combination [6, 9] while maintaining full functionality.

5.4.3.2 - Interfaces

The final source of metrics for this study is related to interfaces.

> <u>Definition:</u> An Interface is a spatial region where energy and/or material flow between components or between a component and the external environment. [8]

Within effort flow analysis, an interface is further characterized by the type of relative motion that occurs. The four possibilities were defined previously as: no relative motion (N-Link), component relative motion (C-Link), general relative motion (R-Link), and interface relative motion (I-Link). These interfaces represent another important indicator

of the degree of integration for a product. The fewer physical interfaces that exist, the more integrated the product is, and hence the further along the product is in the evolutionary process. The number and types of interfaces found in a product can be represented in several ways. An adjacency matrix is used to capture the product interfaces, and a series of relative motion indices (Equations 4.1 – 4.5) are used to measure the composition of the interface characterizations in the product.

$$N-Link\,Index = \frac{\text{Number of N - Links}}{\text{Number of Internal Interfaces}} \tag{5.1}$$

$$C-Link\,Index = \frac{\text{Number of C - Links}}{\text{Number of Internal Interfaces}} \tag{5.2}$$

$$R-Link\,Index = \frac{\text{Number of R - Links}}{\text{Number of Internal Interfaces}} \tag{5.3}$$

$$I-Link\,Index = \frac{\text{Number of I - Links}}{\text{Number of Internal Interfaces}} \tag{5.4}$$

$$Integration\,Index = \frac{\text{Number of Components}}{\text{Number of Internal Interfaces}} \tag{5.5}$$

Each of the metrics collected and analyzed in this study is presented in Table 5.3 along with the use for the metric. Now that the target information is known, the approach to gathering the data must be set forth in the form of a step-by-step procedure that outlines the conduct of the study.

Table 5.3: Empirical Product Study Metrics

Metric	Uses
Number of Functions	Function / Component Matrix
Number of Components	Function / Component Matrix Integration Index Adjacency Matrix DOF's per component comparison
Number of Internal Interfaces	Adjacency Matrix N-Link Index C-Link Index R-Link Index
Number of External Interfaces	Adjacency Matrix
Number of N-Links	N-Link Index
Number of C-Links	C-Link Index
Number of R-Links	R-Link Index

5.4.4 - Procedure

A block diagram representation of the procedure used in the empirical study is shown in Figure 5.1. To understand the chart, follow the arrows downward in the direction of the flow, the main process steps are contained in those boxes attached to the arrows, while the boxes attached to the main steps contain information that is more detailed. The steps at the bottom of the chart are parallel processes, where the product model is analyzed using effort flow analysis, and is scrutinized for graph structures that lead to known solutions for product evolution. What this parallelism tries to highlight is the fact that hypotheses and observations about the evolutionary process will come as the decomposed product is analyzed. What is difficult to capture in a flow chart is the fact that guidelines are discovered all along the way between the start and the end. Whenever one of these discoveries occurs, it should be captured and documented.

It is interesting to note that effort flow analysis is being used within the loop of the study. The significance of this fact is that the object of the study (effort flow analysis) is being used to further its own evolution. This highlights the ability of the method to capture knowledge. In this sense, effort flow analysis is a *living* method capable of evolving. This behavior is not unheard of; one of the fundamental premises of artifact theory is that evolutionary design methods are able to capture design knowledge for later use in other design efforts [121], thus placing effort flow analysis squarely in the

realm of artifact theory methodologies. Although the scope of this study is limited to products in the mechanical domain, the ability of the method to evolve may lead to its application in other product domains. The following sections step through the process of Figure 5.1.

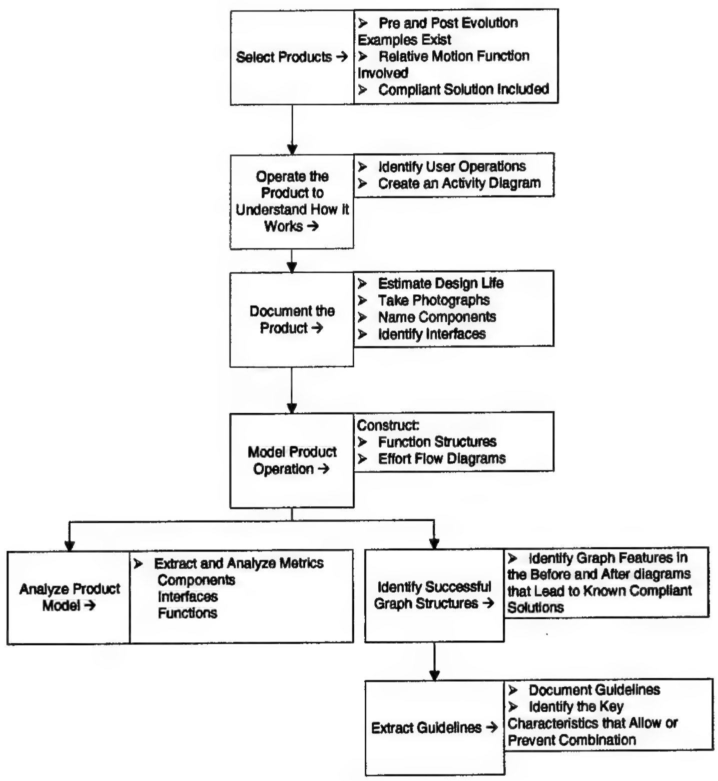


Figure 5.1: Empirical Study Process

5.4.5 - Empirical Study Process Plan

5.4.5.1 - Product Selection

The first factor in selecting a product for inclusion in the study is the presence of relative motion related functionality. In particular, relative motion functionality provided by a compliant mechanism is sought. The second factor is the presence of a clear evolutionary path between the original and other products in the group. The process is deductive in nature; the evolved products are identified first, and then an original product

is sought. The original product has limited or no use of compliance in providing the relative motion function, while there is significant use of compliance in the evolved product.

The goal of product selection is to choose products that represent the application of compliant mechanisms in the mechanical domain. The products are selected for their potential to provide the broadest insights possible for a wide range of mechanical design applications. By representing as much of the mechanical domain as possible, the study provides insight about where and why compliant mechanisms are used.

An alternate approach to product selection method used here is to define a set of relative motion function-flow pairs that is sought. Then, use the basis conditions of coverage, repeatability, and statistical significance as the basis for selection.

In either case, once a product is chosen for inclusion in the study, efforts are made to select competing products from the marketplace. The original and competing products are then classified as a product group. The products within a group are then classified as either an original or an evolved product. In all, there are 16 product groups ranging from two to as many as six products, with the entire study containing 16 original products and 33 evolutions of those products. The product groups and each of the individual products within each of the groups are contained in Appendix C.

5.4.5.2 - Product Operation

Once a product group is selected, the user operations are deduced. The preferred approach to determining the user operations is to operate the product under normal operating conditions. Although other uses are possible, product operation implies that the product is used in a manner consistent with its intended use. Operation of the product identifies the user operations, and those operations are then documented in an activity diagram as defined in Section 4.3.4.

The activity diagram can, and will, have operations associated with many aspects of the product life cycle. In the study, the activity diagrams focus primarily on the user operations that involve the relative motion functions that led to selection of the product to begin with.

In some cases, it is possible that an original and an evolved product will provide a slightly different set of product functions. In these cases, the product providing more user functions will most likely allow more user operations. Only those user operations that are shared by all products in the product group will be used in developing the effort flow diagram, and consideration is given to possible influences from the additional functionality.

5.4.5.3 - Product Documentation

Documentation continues throughout the study, but begins with an initial set of actions taken during product decomposition. Documentation begins with taking photographs of the assembled product and later in the disassembled state. The next documentation step is to name the components of the product, preferably using the naming convention of Appendix A. The component names are tabulated for later use in developing the component-function matrix. Next, the external and internal interfaces are identified for the product. Finally, an estimate of the design life is made for the product.

5.4.5.4 - Product Modeling

Using the activity diagram as a guide, functional models are developed. A general functional model is created for each product group, with particular attention paid to modeling the functions involved with relative motion. Note that only one functional model is created for a product group. Functional modeling is form independent; hence, one model represents the entire product group. This form independent nature is not true for the effort flow diagram.

Modeling continues with the development of effort flow diagrams for all products in the product group. As discussed earlier in the dissertation, the effort flow diagram is a schematic representation of the components of the product and their interaction while in operation. The benefit of using a schematic representation in the study is two fold. The first is that the observed results that come from the analysis are framed in the effort flow analysis nomenclature and therefore directly applicable to furthering the development of the method. The second and possibly greater benefit is that a schematic representation has the ability to represent the components in an abstract

manner that excludes all the physical information except the topology [89]. This abstract representation allows generalization of the observations to other products that have the same or similar topology independent of the particular form of the components that make up the product.

In developing the effort flow diagrams, only those user operations involved in generation of relative motion within the product are modeled. This selectivity leads to a less complex diagrams, and follows from the idea that the activity diagram is more detailed for the operations that affect the user operations of interest and less detailed for the other operations. This approach to activity diagram development is discussed in Chapter 3.

5.4.5.5 - Product Analysis

The first step taken in analyzing each product is to extract and analyze the study metrics; these are the same metrics discussed earlier and shown in Table 5.3. Collection of the metrics themselves is the relatively simple matter of counting the number of functions and components of the product, and counting the number and types of links in the effort flow diagram. Capturing the relationship between the components and the functions is a more difficult matter.

Each product is analyzed to correlate components of the product to the functions they provide. The assumption here is that the product in question is the result of design synthesis process that followed a path from prescribed functions to resulting forms [122]. The process of deducing the component-function relationship is based on observing the behaviors of the product as it is operated in its intended environment. A *behavior* is defined as the physical manifestation of a product function [122]. Clearly, the process of mapping components to functions is subjective, and the results will show some variability.

The results of the component-function mapping are recorded in a table where the rows contain the basis function names, and each column represents a product. The cells of the table are filled in with the name of the component providing a particular function for the product under consideration. Some cells may contain the names of one or more components, and some components may show up in more than one cell. The case of

more than one component providing a single function may imply a module, and the case of one component providing multiple functions implies function sharing in the component. As the function structure and component-function matrix is completed, insight about the interaction between the components is generated and used in the next analysis step.

Another area of interest is gaining insights and data relating to key characteristics that may be used to determine the feasibility of component combination. These insights are taken predominantly from analysis of the original product. Examples of key characteristics in the original product are related to: stress, strain, toughness, thermal stability, design life, cyclic loading environment and creep to name a few. The goal is to identify the relationship between these key characteristics and the product modeling required to develop the evolved product.

5.4.5.6 - Search for Successful Graph Features

At every step in the study process, the product and its models (functional and effort flow) are scrutinized for potential insights that may lead to design guidelines. The key factor in making these insights possible is the side-by-side decomposition and analysis of the original and evolved products.

The hypothesized design guidelines that result from this study are deduced from comparisons of the effort flow diagrams for the original and evolved products. Particular attention is given to searching for instances where the fundamental effort flow guidelines are evident. The reason for this focus is to strengthen evidence of their fundamental status in the method. The more often these guidelines are observed, the greater the strength of evidence to support them. In addition to supporting the fundamental guidelines, evidence to support guidelines previously recorded during the analysis of other product groups is also sought. Finally, new guidelines are sought in the graph structures for the current product group.

5.4.5.7 - Guideline Extraction and Generation

Engineering design guidelines are deduced from two sources, the identified graph structures just discussed, and observations about the key characteristics that allow or prevent component combination.

Graph structure based guidelines are deduced using a process that French calls visual thought [113], where the designer projects the evolutionary path from the original product through intermediary steps to the evolved product. Path projection for this study is carried out in the reference frame of the node and link graphical elements. The resulting insights are the kernels for product evolution guidelines.

Key characteristics based guidelines are deduced using observations about such intangibles as the designers intent and motivation. Other sources of insights include published literature and expert opinion on the design and synthesis of compliant mechanisms.

The approach to extracting guidelines that are specific to effort flow analysis begins with a comparison of the effort flow diagrams for all versions of the product. The guidelines that result from this comparison are based on identifiable and classifiable graph structures that represent "flags" or indicators of component combination opportunities. The goal then is to identify localized graph structures where successful evolutionary transformations occurred between the original and the evolved products. A graph structure transformation is successful if it leads to the instantiation of a compliant mechanism solution in the evolved product.

Once the graph regions are identified in the original and evolved diagram, the highlighted region of the original diagram is manipulated to transform the original effort flow diagram to one that is graphically equivalent, or isomorphic, to the diagram for the evolved product. The graph manipulation steps and key characteristics required to achieve this graph transformation are recorded and generalized into a recommendation that forms a design guideline. This transformation and generalization process infers a relationship between the observed differences in the graphs and design principles that explain them.

5.4.5.8 - Product Group General Observations

In generating the design guidelines from each product group, some observations do not fit neatly into a particular graph structure guideline. For observations of this type, a section of the empirical study is devoted to general observations about the product and its evolution. These observations are collected for their value in modifying existing guidelines, and in generating altogether new guidelines. In essence, the General Observations section of the study is a "catch all" for potentially useful captured design knowledge.

Having defined the guideline theory as well as the empirical study methodology and metrics, the process of collecting the hypothesized guidelines is demonstrated via a complete example for one of the product groups in the study.

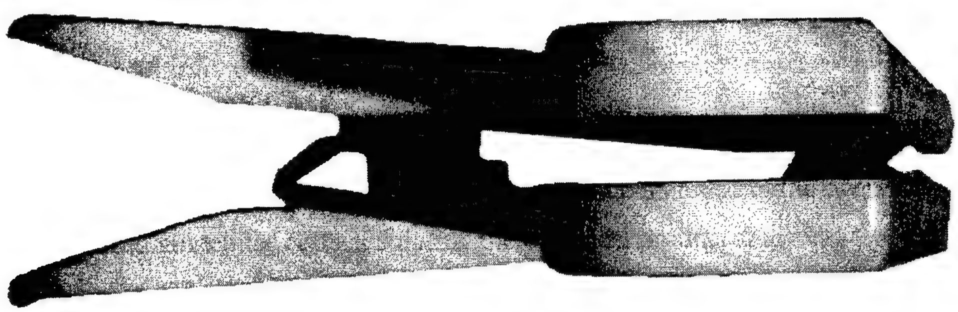
5.5 - PRODUCT STUDY CASE

The results for a Kitchen Clip product group used in the study are presented here in their entirety. The results for this product will then be included in the overall table of all hypothesized guidelines collected during the empirical product study.

5.5.1 - Product Selection, Documentation, and Modeling

5.5.1.1 - Product Selection

Initial product selection is based on the existence of the baseline product, Figure 5.2, and an evolved product, Figure 5.4. The operations that will be modeled in the effort flow analysis are based on the activity diagram of Figure 5.3, where the activities selected for inclusion are those operations associated with the end user. Assembly is not considered, as the evolved product has no assembly activities. Hence, an improvement in assemblability has already been achieved.



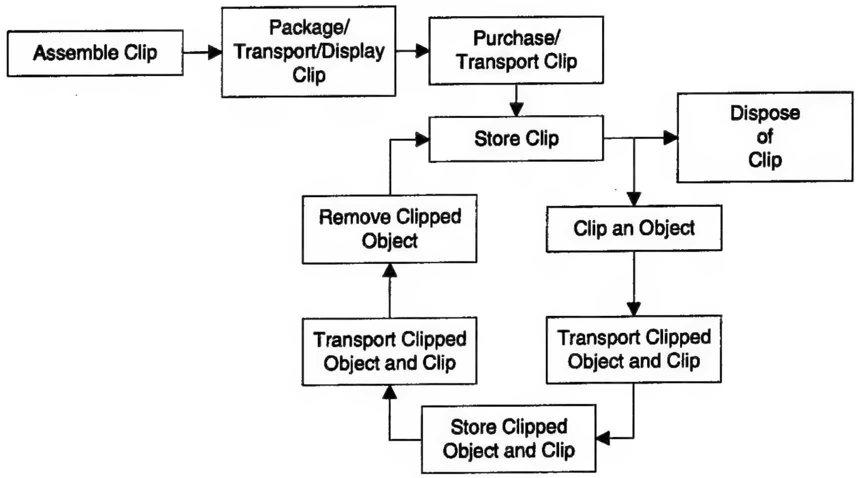


Figure 5.3: Kitchen Clip Activity Diagram

5.5.1.2 - Product Documentation

The product is documented to include the component names in Table 5.4, the interfaces are represented in the adjacency matrices of Table 5.5 and Table 5.6, and pictures of the products are shown in Figure 5.4. Note that the adjacency matrix for the evolved product only has on row and one column. This reflects the fact that the product only has one component. The difficulty is that that one component has both external interfaces with the environment and an internal interface with itself in the latch area. To capture this fact, an "E" and an "I" are annotated in the cell. If this were a redesign effort rather than a data gathering effort, representing the product using functional components might offer more insights.

Table 5.4: Product Components and Names

Comp ID	**Product Components**	
	Original	**Evolved**
1.	Arm #1	Hinged Beam
2.	Arm #2	
3.	Coil Spring	
4.	Friction Enhancer #1	
5.	Friction Enhancer #2	

Table 5.5: Adjacency Matrix for Original Product

Component Name	Arm #1	Arm #2	Spring (Coil)	Friction Enhancer #1	Friction Enhancer #2
Arm #1	E	1	1	1	0
Arm #2	1	E	1	0	1
Spring (Coil)	1	1	I	0	0
Friction Enhancer #1	1	0	0	E	0
Friction Enhancer #2	0	1	0	0	E

Table 5.6: Adjacency Matrix for Evolved Product

Component Name	Hinged Beam
Hinged Beam	E, I

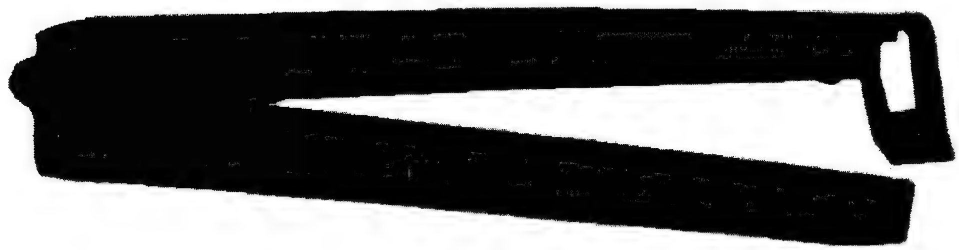


Figure 5.4: Evolved Kitchen Clip Product

5.5.1.3 - Product Modeling

The product-modeling phase leads to the functional model shown in Figure 5.5, and the effort flow diagrams of Figure 5.7. Several points need to be made about the construction of the effort flow diagrams for both products. The first point regards the interfaces between the spring and the arms in the original product. Note that there are two links between each arm and the spring. The spring has continuous contact with the arm at one interface, and intermittent contact with the arm at another interface that is only active during the clip and remove operations.

The second point regards the self-interfacing nature of the evolved clip. The locking feature, provided by an integral attachment latch, transmits effort during some portion of all operations. Based on the definition of interfaces used in effort flow analysis, the relative motion is characterized as an R-Link for the clip and remove operations, and as an N-Link for the store operation. This multi-operation interaction needs to be captured, characterized, and represented. To do so, a link is placed between the hinged beam and itself and is characterized as discussed. From these effort flow diagrams, the analysis, identification, and extraction steps are carried out to deduce design guidelines from the product.

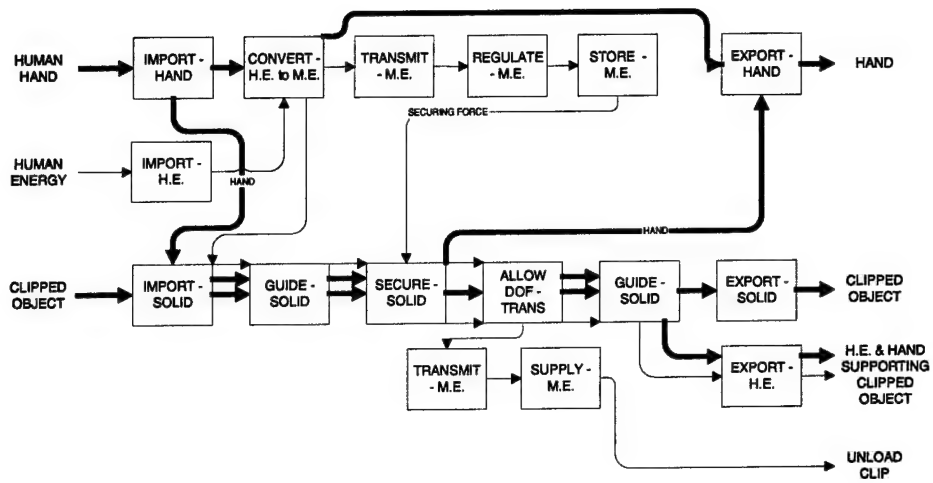


Figure 5.5: Kitchen Clip Function Structure

5.5.2 - Product Analysis, Graph Structures, and Guideline Extraction

5.5.2.1 - Analysis

Analysis of the effort flow diagrams in Figure 5.6 leads to collection of the metrics shown in Table 5.7. These measurements give an indication of how the product changes between the two variants. For example, the Function/Component ratio indicates a significant increase in the function sharing, as all functions of the product are provided by a single component compared to the five components in the original product.

Table 5.7: Measured Indices

Metric	Original Design	Evolved Design	Difference
Number of Components = $\mathbf{N_c}$	5	1	4
Number of Internal Interfaces = **II**	11	1	10
Number of N-Links = **N**	7	1	6
Number of C-Links = **C**	12	0	12
Number of R-Links = **R**	2	2	0
Link Connectivity = $\mathbf{N_c/II}$	0.45	1	
Link to Interface Ratio = **N/II**	0.64	1	-0.36
Link to Interface Ratio = **C/II**	1.09	0.0	1.09
Link to Interface Ratio = **R/II**	0.18	2	-1.82
Number of NR-Links = **NR**	1	1	0
Number of NC-Links = **NC**	6	0	6
Number of RC-Links = **RC**	0	0	0
Number of External Interfaces = **IE**	4	4	0
Number of Functions = **F**	14	14	0
Function/Component Ratio = $\mathbf{F/N_c}$	2.8	14	
Number of Operations Modeled = $\mathbf{N_o}$	3	3	

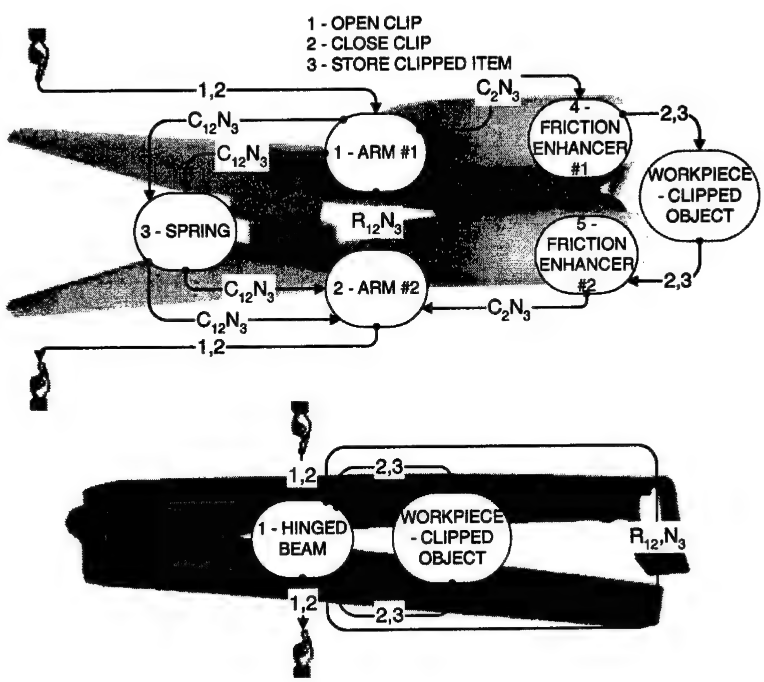


Figure 5.6: Effort Flow Diagrams for the Kitchen Clip Product

The next step in analyzing the product is to correlate functions with components in the product. This step is done using a table with functions in the rows and products in the columns. The results for the Kitchen Clip product are in Table 5.8. Note that only functions provided by the product are shown in the table. Also, note that several functions have multiple entries resulting from the fact that a function may be provided for more than one flow in a single product.

Table 5.8: Relative Motion Functions and Components Involved

Basis Function	**Flow**	**Associated Components**	
		Original Design	**Evolved Design**
Actuate			
Allow DOF	Translation	Arm #1 & #2, Friction Enhancer #1 & #2	Hinged Beam (Living Hinge)
Convert	H.E.→M.E.	Arm #1 & #2	
Export	Hand	Arm #1 & #2	Hinged Beam (Beam)
	H.E.	Arm #1 & #2	Hinged Beam (Beam)
	Solid (Clipped Object)	Friction Enhancer #1 & #2	Hinged Beam (Beam, Latch)
Guide	Solid (Clipped Object)	Arm #1 & #2, Friction Enhancer #1 & #2	Hinged Beam (Beam)
Import	Hand	Arm #1 & #2	Hinged Beam (Beam)
	Human Energy	Arm #1 & #2	Hinged Beam (Beam)
	Solid (Clipped object)	Arm #1 & #2, Friction Enhancer #1 & #2	Hinged Beam (Beam)
Regulate	M.E.	Arm #1 & #2	Hinged Beam (Beam)
Secure	Solid (Clipped Object)	Friction Enhancer #1 & #2	Hinged Beam (Latch, Hinge, Beam)
Store	M.E.	Coil Spring	Hinged Beam (Beam)
Supply	M.E.	Coil Spring	Hinged Beam (Beam)
Transmit	M.E.	Arm #1 & #2	Hinged Beam (Beam)

5.5.2.2 - Successful Graph Structures

The process of guideline generation proceeds by comparing the two effort flow diagrams in Figure 5.7, paying particular attention to regions of the graph where the fundamental guidelines may be implemented in the original product. There are no N-Link, C-Link, or R-Link groups for this product, hence none of the fundamental

guidelines can be verified. The next step is to look for contractions of the original graph that could lead to the evolved graph.

The dominant link configuration in the original graph is the $C_{12}N_3$, which is observed in six of seven internal interfaces. Looking at the evolved graph, the only internal link type that remains is a single $R_{12}N_3$. The total absence of the $C_{12}N_3$ in the evolved product raises a flag that a relationship exists between this link type and an effort flow guideline. Possible cases include guidelines concerning parallel links, the precedence of one link characterization over another, and relationships between the link type and the function it provides.

A final observation on the graph structures will highlight the difficulty in generalizing about how a possible guideline might be deduced. The difficulty is associated with relationship between the $R_{12}N_3$ link between the arms of the original and evolved products.

Do the features associated with the links remain in their original form as the model is evolved from original to evolved forms? The original product uses the $R_{12}N_3$ link to constrain a DOF in the hinge between the arms; the evolved product uses the $R_{12}N_3$ link to provide a releasable locking behavior. There are similarities between the functions provide by each, but their behaviors are decidedly different. The functions provided are to transmit force and to allow a DOF. Both of the features associated with the links must resist the clamping force exerted on the clamped object and both features are involved with providing the allow DOF function. The behavior exhibited by each feature in providing the transmit effort function is to resist a compressive force in the original product and a tensile force in the evolved product. The differences between the behaviors associated with providing the allow DOF function are more stark; the original product provides a single DOF in the form of hinge or revolute joint, while the evolved product constrains a DOF in the form of an integral locking feature. Both are related to the allow DOF function, but the forms and behaviors are very different.

The point in detailing this aspect of this product group is to highlight the danger in making hasty conclusions that might lead to invalid design guidelines. It is possible that a guideline regarding the combinability across CN links that are parallel to RN links might have been made based on the incorrect assumption that the RN link continued to

exist in the evolved product. Unfortunately, that link did not remain; rather it was a new link created in the evolved product.

A valid guideline that can be derived from this discussion is that the "DOF-based-functions provided in the original product must also be provided in the evolved product." This example highlights the fact that creative solutions on the part of the designer are still a necessary aspect of redesign using effort flow analysis, effort flow analysis merely channels the focus of that creativity to areas where it can be made most effective. Looking back at the flagged areas of the diagram previously discussed does lead to several hypothesized product evolution guidelines as follows.

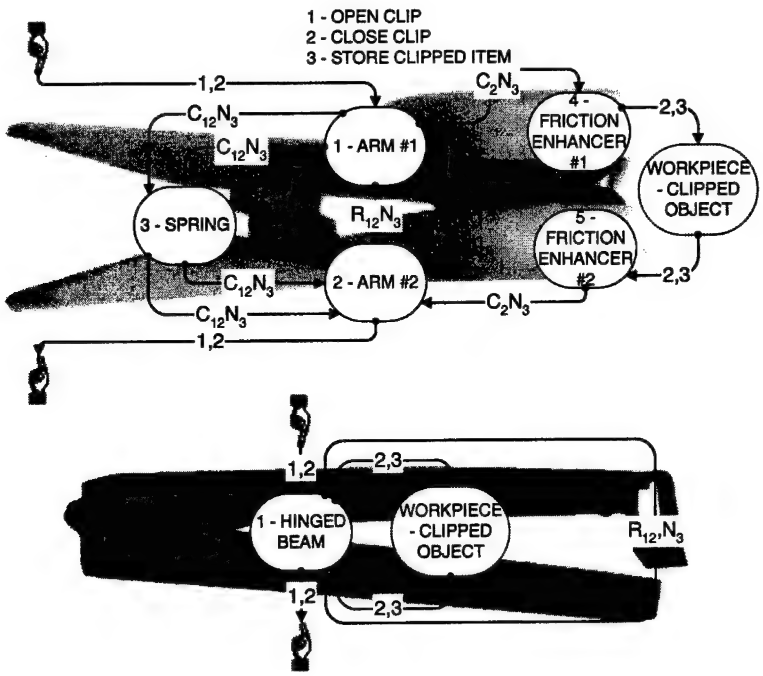


Figure 5.7: Effort Flow Diagrams for the Kitchen Clip Product

5.5.2.3 - Hypothesized Guidelines

The following guidelines are the observations made during analysis of this product group followed by the final version of the guidelines to which they contributed.

Guideline: Use distributed compliance to replace the energy storage functionality of a spring, see Table 5.9.

Table 5.9: Distributed Compliance Guideline

DISTRIBUTED COMPLIANCE	
Recommendation	Architectures dictating that broad regions of a device be compliant are classified as distributed compliance problems.
Guideline steps	The analysis and synthesis of distributed compliant mechanisms where multiple components move in a relatively complex load and deflection environment is best carried out using continuum models for analysis. The analysis of distributed compliant mechanisms where fewer components move in relatively uncomplicated load and deflection environment is best carried out using the pseudo-rigid body model. CONTINUUM MODEL: The continuum model approach to the synthesis of distributed compliant architectures is typically a search using finite element modeling (FEM). The approach is to first define the boundary conditions for the compliant mechanism in terms of the locations, directions, and magnitudes of forces and deflections based on the envelope occupied by the components selected for combination in the original product. A fully populated mesh is defined to occupy the region of space available for the mechanism. The region is based on the envelope defined by the components in the original product. The loads or deflections expected or desired in the compliant mechanism are then imposed on the mesh. For applications where a minimum resistance to motion is required, the elements are manipulated so that strain energy is minimized for the overall mesh. For applications where energy storage is required, the elements are manipulated so that strain energy hits a target value for the overall mesh. PSEUDO-RIGID BODY: The pseudo-rigid body model approach treats the elements of the compliant mechanism as rigid members connected by pin joints. Each joint is modeled as a revolute joint and a spring, where the spring represents the strain energy of the compliant mechanism. Two possible considerations in the synthesis compliant mechanisms using bending beams in the pseudo-rigid body model are the relationships between the second moment of area and the bending stress, and between the length of the compliant member and the bending stress. See the criterion entries below for guidelines related to length and

	second moment of area. Once the topology of the mechanism is determined using either the continuum model or the pseudo-rigid body approach, apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	
Criterion	Apply the I vs. BENDING STRESS guideline. Apply the Length vs. BENDING STRESS guideline.
Supplemental material	Solution Examples Kitchen Clip
References	Continuum Model: [24, 36-41, 44, 45, 123-126] Pseudo-Rigid Body Model: [29-32, 34, 42, 43, 127-130] Bistable Mechanisms: [35, 131] Mechanical Advantage: [27]
Guideline Support	

Guideline: Use living hinges to provide the Allow-DOF function in tensile loading applications, see Table 5.10.

Table 5.10: Localized Compliance Guideline

LOCALIZED COMPLIANCE	
Recommendation	Compliant solutions dictating that the small regions of the device be compliant are classified as Localized Compliance problems. Compliant mechanisms of this type are best analyzed using the pseudo rigid-body model.
Guideline steps	PSEUDO-RIGID BODY: The pseudo-rigid body model approach treats the elements of the compliant mechanism as rigid members connected by pin joints. Each joint is modeled as a revolute joint and a spring, where the spring represents the strain energy of the compliant mechanism. For mechanisms where the strain energy is to be minimized, the spring stiffness should be negligible in comparison to the other forces that act in the mechanism. Several rotation based mechanisms are possible to replace pin joints: Living Hinge, Assembly Hinge, Passive Joints (separate components maintained in contact by compressive forces), Q-Joints, Cross Axis Flexural Pivots, Torsional Hinges, and Split Tube Flexures. Each of these types of compliant joints is discussed in detail in the references given below. Once a joint replacement configuration has been chosen, apply

	the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Compliant *living hinge* joints are inappropriate in applications where large compressive loads must sustained, as the compressive load causes the hinge section to buckle. Compliant *living hinge* joints are inappropriate in applications where the compliant joint must provide an energy storage function.
Criterion	Compliant joints are inappropriate in applications where the magnitude of rotation, $\boldsymbol{\theta \geq 360°}$.
Supplemental material	Solution Examples: Kitchen Clip
References	Living Hinge, [29, 127, 132, 133] Assembly Hinge, [132] Passive Joints, [29] Q-Joints, [28] Cross Axis Flexural Pivots, [134] Torsional Hinges, [29] Split Tube Flexures [135]
Guideline Support	

Guideline: C-Links and N-Links that are coincident on an interface are combinable provided the required force transfer and DOF constraint provided by the N-Link can be achieved using a compliant member, see Table 5.11. Component combinations of this type appear to be a melding of the 1st and 2nd order fundamental guidelines. Evidence for this guideline is in the structure at the top of Figure 5.7 where the arms and spring are combined to produce the beams, hinge and latch in the evolved product at the bottom of Figure 5.7. In this case, the DOF constraint is changed from resisting a compressive load in the original product to resisting a tensile load in the evolved product. In addition, the constraint on out-of-plane motion enforced by the interface between the arms of the original product is enforced by the hinge and latch of the evolved product.

Table 5.11: C & N Coincident on a Single Link

CN-LINKS	
Recommendation	CN-Links behave primarily as C-Links; therefore, give higher priority to the contribution of the C-Link in determining a combined solution. CN-Groups are combinable using the C-

	the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Compliant *living hinge* joints are inappropriate in applications where large compressive loads must sustained, as the compressive load causes the hinge section to buckle. Compliant *living hinge* joints are inappropriate in applications where the compliant joint must provide an energy storage function.
Criterion	Compliant joints are inappropriate in applications where the magnitude of rotation, $\boldsymbol{\theta \geq 360°}$.
Supplemental material	Solution Examples: Kitchen Clip
References	Living Hinge, [29, 127, 132, 133] Assembly Hinge, [132] Passive Joints, [29] Q-Joints, [28] Cross Axis Flexural Pivots, [134] Torsional Hinges, [29] Split Tube Flexures [135]
Guideline Support	

Guideline: C-Links and N-Links that are coincident on an interface are combinable provided the required force transfer and DOF constraint provided by the N-Link can be achieved using a compliant member, see Table 5.11. Component combinations of this type appear to be a melding of the 1st and 2nd order fundamental guidelines. Evidence for this guideline is in the structure at the top of Figure 5.7 where the arms and spring are combined to produce the beams, hinge and latch in the evolved product at the bottom of Figure 5.7. In this case, the DOF constraint is changed from resisting a compressive load in the original product to resisting a tensile load in the evolved product. In addition, the constraint on out-of-plane motion enforced by the interface between the arms of the original product is enforced by the hinge and latch of the evolved product.

Table 5.11: C & N Coincident on a Single Link

CN-LINKS	
Recommendation	CN-Links behave primarily as C-Links; therefore, give higher priority to the contribution of the C-Link in determining a combined solution. CN-Groups are combinable using the C-

<table>
<tr><td></td><td>Group Guideline approach provided the required constraint on the DOF needed for the N-Link is achieved.</td></tr>
<tr><td>Guideline steps</td><td>Identify interfaces where one or more CN-Links occur.
Treat the CN-Group as though made up of C-Links only.
Combine the components connected by CN-Links by removing the link and joining the nodes into a compliant mechanism.
Apply the MATERIAL SELECTION guideline to the combined component.</td></tr>
<tr><td>Branch steps</td><td></td></tr>
<tr><td>Conditional steps</td><td>Apply the NECESSARY CONDITIONS guideline to the combined component.</td></tr>
<tr><td>Criterion</td><td></td></tr>
<tr><td>Supplemental material</td><td>Solution Examples:
This guideline is evident in the structure of the kitchen clip product. Combination of the arms and spring produces the beams, hinge and latch in the evolved product of Figure 5.8. The DOF constraint is changed from resisting a compressive load in the hinge of the original product to resisting a tensile load in the hinge of the evolved product. In addition, the constraint on out-of-plane at the interface between the arms of the original product is enforced by the hinge and latch of the evolved product.

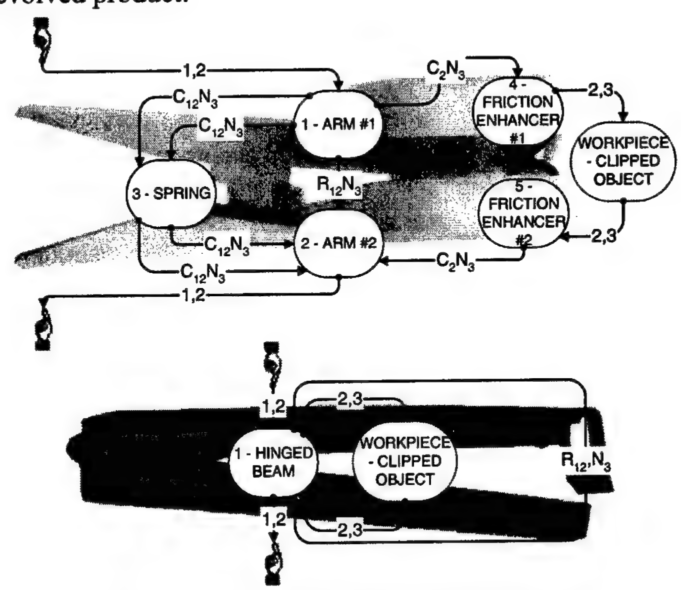


Figure 5.8: CN-Group structure in graph</td></tr>
<tr><td>References</td><td></td></tr>
<tr><td>Guideline Support</td><td></td></tr>
</table>

<u>Guideline:</u> Components connected by R-Links and N-Links that are coincident on the same link are combinable using compliance when the DOF required for the R-Link

and the DOF constraint for the N-Link can be maintained in the contracted component. A combination of this type appears to be a combination of the 1^{st} and N^{th} order fundamental guidelines.

Table 5.12: R & N Coincident on a Single Link

RN-LINKS – COMPLIANT COMBINATION	
Recommendation	RN-Links behave primarily as R-Links; therefore, give higher priority to the contribution of the R-Link in determining a combined solution. RN-Groups are combinable using the guidelines that treat various instances of the R-Link while continuing to provide the constraint behavior provided by the N-Link.
Guideline steps	Identify one or more RN-Links. Replace separate components connected by an RN-Link with a single compliant mechanism using the guideline that is appropriate for the R-Link configuration. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Kitchen Clip
References	
Guideline Support	

<u>Guideline:</u> R-Links in parallel with energy storage C-Links are combinable using compliant components as long as the required strength, energy storage and DOF can be maintained in the contracted compliant component.

Table 5.13: Parallel R & C-Link Combination

PARALLEL R & C LINK COMBINATION	
Recommendation	Combine parallel R-Links and C-Links by incorporating the Allow DOF function of the R-Link with the Store Energy function of the C-Link into a single compliant mechanism.
Guideline steps	Identify parallel R & C Links in the graph structure; these may also be RN & CN Links. Generate design concepts to combine the R-Linked components into a compliant mechanism.

Generate design concepts for the combination of the C-Grouped components that now includes the former R-Linked components.

Possible solutions to the C-Group combination can come from the C-LINK WITH STRAIN ENERGY STORAGE guideline.

An example is shown in Figure 5.9where the original C-Group contains energy storage C-Links in parallel with R-Links, and the evolved diagram is shown in Figure 5.10 .

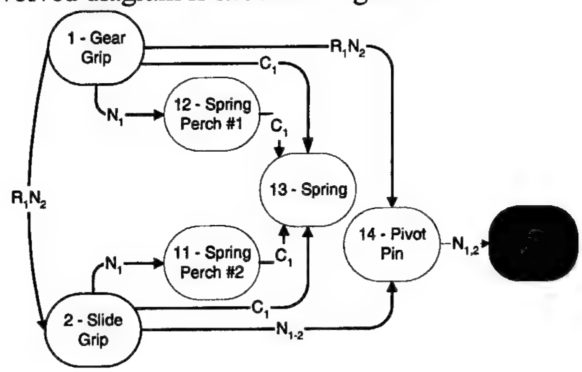


Figure 5.9: Graph Structure for Parallel R & C Links

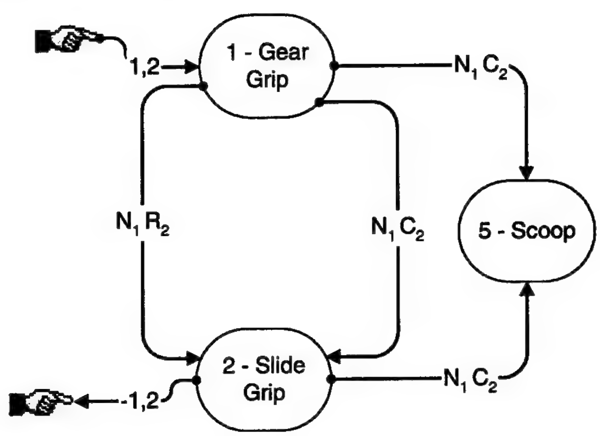


Figure 5.10: Graph Structure for Evolved Parallel R & C Links. Note, one R-Link is maintained in this product due to functional constraints.

Apply the MATERIAL SELECTION guideline to the rigid body combined component.

Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	Parallel Structures are effort flow paths that originate at a single node and end at another single node without branching in between.
Supplemental material	Solution Examples: Kitchen Clip, Clothespin, and Ice Cream Scoop products
References	
Guideline Support	**

5.5.2.4 - Product Group General Observations

The evolution of this product results in a fully monolithic combination. The solution embodied in the evolved product is non-intuitive, as the evolved product is not a parametric redesign of the original product. The guidelines extracted from this product group attempt to capture the knowledge necessary to implement similarly unique solutions in other products.

The visco-elastic creep behavior due to the relatively long loading times for the beams and hinge area (days or weeks) is acceptable for this product because the accuracy requirements for the successful operation of the product are very low. The clamping force can be reduced significantly without significant degradation in the function of the product. All that is required is that the clip not allow air to enter the container, in this case the container is generally a bag.

Table 5.14: Time Dependence in Compliant Polymers

TIME DEPENDENT BEHAVIOR IN COMPLIANT POLYMERS	
Recommendation	Avoid the use of polymer compliant mechanisms in applications where the mechanism is subject to sustained loads or deformations.
Guideline steps	Determine whether the combined component is to operate under sustained loading or sustained deformation. If either of the two previous conditions is true, visco-elastic behavior may result in the mechanism. Apply the MATERIAL SELECTION guideline to the combined component. If visco-elastic behavior is undesired, take one of the following mitigation approaches: a. reconfigure the design so the compliant polymer mechanism doesn't support sustained loads or deformations under normal operating conditions, or b. replace the polymer with a material not susceptible to visco elastic effects, or c. consider the addition of a non visco-elastic support mechanism.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Kitchen Clip
References	[29, 129, 136, 137]
Guideline Support	

One of the primary factors leading to this combination is the relatively low force needed to provide the clamping function in the original product. In the original product, the energy to secure the clipped object is stored in the spring. The resulting force acts through the arms using the hinge point as a fulcrum to clamp the object between the friction enhancers. In the evolved product, energy for securing the clipped object is stored in the deformed beams. The resulting force acts against the living hinge and integral latch to clamp the object between the beams. The insights gained through this observation contribute to several guidelines, including those given in Table 5.9 and Table 5.10.

The four guidelines that resulted from this example are representative of the process carried out for all the product groups. Each product lead to the direct generation

of guidelines, lent support to previously established guidelines, and provided insights leading to still more design guidelines. The next section provides a discussion of the validity of the guidelines presented, followed by a laundry list of all the guidelines generated during the empirical study.

5.6 - VALIDITY ANALYSIS

Validation of the knowledge collected in the guidelines presented here is based on two premises. The first premise is based on deductive reasoning. Let the collection of "original" products from each product group be represented as a set of problems ***P***, let the collection of all evolved products be represented as a set of solutions, ***S***, and let the captured knowledge extracted from all the product groups be represented as a set of guidelines ***G***. The knowledge collected in ***G*** is valid if a solution ***x*** which is a member of ***S*** results when ***G*** operates on any member of ***P***. This relationship is shown in Equation 5.6.

$$G \rightarrow P : x \subset S \tag{5.6}$$

This approach to validation is similar to that used by Chakrabarti & Bligh [99] in their work on functional synthesis in mechanical design. In their work, a set of algorithmic solutions relevant to the automated synthesis of primitive mechanical transmissions (similar context to this work) was developed and tested with good success. In support of this approach to validation, each guideline hypothesized in this work is the result of an observed solution to the problem presented by the original product in each product group; in fact, several of the guidelines are observed in nearly all the product groups studied.

The second premise to the validation approach is based on an analysis of the number of new guidelines generated as each successive product group is analyzed. The results are presented in Figure 5.11, where the total number of new guidelines on the abscissa, and the product names on the ordinal. The product names are presented in the order they were analyzed, and the new guidelines are those that had not been observed before. The desired result is that the curve will approach a horizontal asymptote indicating that no new design guidelines are generated with the addition of a new product to the study population. An asymptotic result indicates that few new guidelines are available for extraction for the domain of products considered in the study, but is not an

absolute indication that no new insights are available. In fact, new insights were gained with each new product group, and the known guidelines continued to be refined as new products were added to the study, but refinements were not treated as "new guidelines." The results shown in Figure 5.11 indicate that this study has indeed reached an asymptote in the number of new guidelines gleaned from each new product, as no new guidelines were extracted in the last several product groups evaluated. There is admittedly some bias in this approach, as the extraction of guidelines is dependent upon the deductive reasoning power of the observer. To address this bias, three of the product groups were evaluated by a second observer, and the results were compared for consistency. The net result is that each observer gathered essentially the same guideline information, with subtle differences based on the personal expertise of each person.

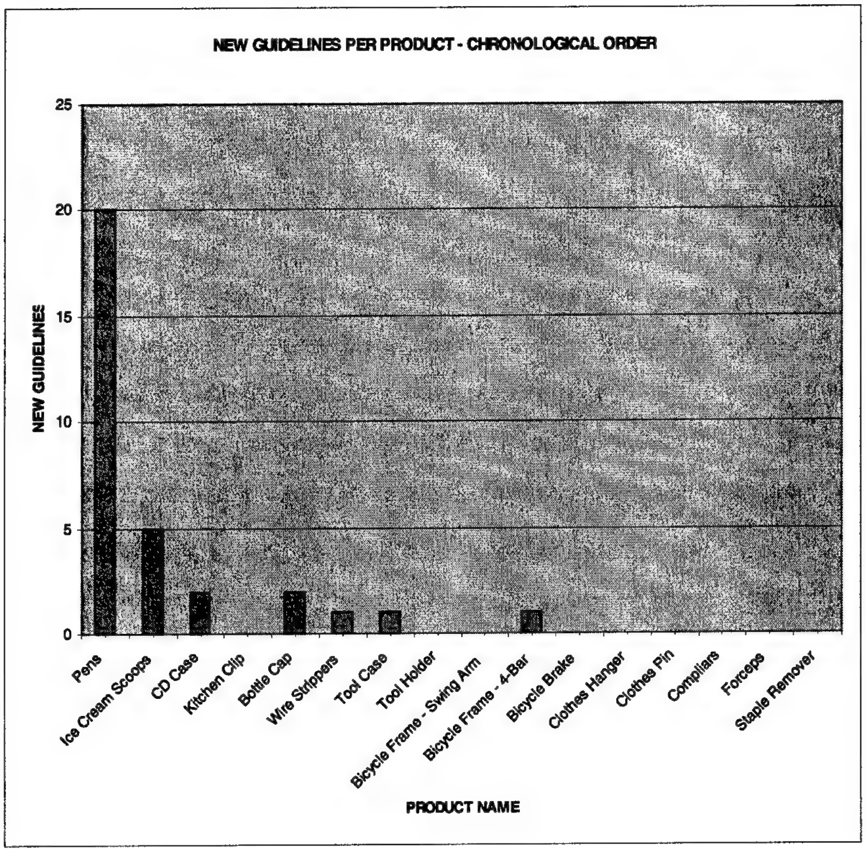


Figure 5.11: New Guidelines Extracted per Product (Chronological Order)

While not completely rigorous, the results of this validity analysis are sound and reasonable in light of the definition for heuristic design rules, the essence of which is that a design heuristic works often enough to make it worth applying to problems where it is appropriate. Setting aside the validity question, the design guidelines here derived are addressed.

5.7 - Overall Guideline Results

The guidelines developed through this study are relatively broad in scope, ranging from those treating the specific case of parallel R and C-Links to those that address the process of selecting an appropriate compliant mechanism synthesis technique. Each has proven to be useful in at least one product group, while many are applicable in

nearly all the product groups. The body of the collected guidelines are presented in their entirety in Appendix B.

The value of the guidelines in Appendix B stems from the fact that they represent the embodiment of collected compliant mechanism design knowledge for a range of products. The products range from mundane bottle caps to exotic titanium mountain bike frames, but the applicability of the guidelines is not limited by the products from which they were wrought. The resulting set of heuristics are claimed to apply across a much broader range of artifacts. This broad applicability in the guidelines implies that insights gained from analysis of the ice cream scoop may find application in the design of future spacecraft.

As a first step in fostering the use of the effort flow analysis design guidelines in a product design environment, the guidelines in Appendix B are categorized by the order of the guideline beginning with the 1st order guidelines, based primarily on the N-Link, then the 2nd order guidelines, based primarily on the C-Link, and finally the Nth order guidelines are presented. In addition to the categorization, the short hand notation presented in Table 5.15 is used in the guidelines as well. The short hand deals with the link notation used for guidelines where multiple characterizations are present. The notation condenses the description, and removes any references to operations that might be in an effort flow diagram.

Table 5.15: Table of Short Hand Notation for Guidelines

Active Links	Notation
R-Link and N-Link both active	RN-Link
C-Link and N-Link both active	CN-Link
R-Link and C-Link both active	RC-Link
R-Link, C-Link and N-Link all active	RCN-Link

Chapter 6 - Effort Flow Analysis

6.1 - INTRODUCTION

Effort flow analysis began as a simple idea that is given stability through the construction of a theoretical foundation based on Newtonian mechanics and graph theory. The foundation is used as a base for the development of a detailed procedure for directed product evolution. Using the overall structure of the procedure as a framework, a set of product evolution guidelines are built by executing an empirical product study. The guidelines, used in the context of the effort flow analysis methodology, provide direction to the evolution of mechanical artifacts in a redesign environment.

At this point in its development, effort flow analysis has evolved to a point where it is possible to discuss a "Theory of Effort Flow Analysis." The theory provides the overall context for use of the method. Once the theory is established and supported, the method can be distilled down to a more useable format. The result of the distillation process is a method that is easily applied to both the original and redesign of real products. With the theory established and a user application in place, the repeatability of the method can be addressed. Repeatability is of particular interest in an industrial sense, as a method that produces repeatable results is one that can be used with confidence when the bottom line is in view.

6.2 - THEORY OF EFA

The theory of effort flow analysis is based on the fundamental tenets from graph theory and mechanics discussed in Chapter 2. Other significant elements in the foundation of effort flow analysis are the theory of technical systems design [49], artifact theory [121, 138], and physical systems modeling [94]. Key elements from these foundational elements come together to form the kernel of the theory of effort flow analysis.

The theory of effort flow analysis supports the fundamental goal of the method, which is to promote directed product evolution through the synthesis of rigid body and compliant mechanism design concepts. The key element of interest in identifying and

promoting product evolution is the physical interactions between components at the interfaces. The main parameter in analyzing interface interaction is the presence or absence of relative motion. Relative motion is key because, traditionally, the requirement for relative motion has dictated that separate components be created. Tradition is important because the effort flow analysis method is framed in the context of product redesign, where redesign implies the evolution of what was done before. Novel redesign solutions are synthesized by observing traditional multi-component solutions from the unique perspective provided by effort flow analysis.

Effort flow analysis approaches product redesign from the perspective that separate components are not needed to provide a relative motion function in a mechanism. In fact, the presence of relative motion in an original artifact marks an opportunity for product evolution through the synthesis of compliant mechanisms capable of providing the required motion. In the domain of mechanical mechanisms, relative motion exists to provide (or constrain) either end-point positioning or path generation. These two behaviors can often times be provided by monolithic or semi-monolithic compliant devices used to construct the artifact, this approach is known as rigid body replacement [29]. Effort flow analysis provides a means of systematically identifying candidates for synthesis of compliant mechanisms for rigid body replacement.

6.2.1 - Overall Framework for Design Problem Solving

The theory of technical systems is a generally accepted and widely used approach in engineering design science. One of the most oft cited references in the theory of technical systems is Pahl & Beitz [139]. In the third edition of their book, Pahl and Beitz present a six phase General Working Methodology [49] as a framework for design problem solving. The relationship between this general framework and effort flow analysis will be highlighted In the following sections.

1. Purposeful thinking – engage in intuitive and discursive thinking processes, these are synergistic with one another. Intuitive thinking requires a significant amount of familiarity with the problem at hand, while discursive thinking relies on a more systematic approach to thinking about the problem at hand. The effort flow analysis methodology contributes to the designers

ability to practice the discursive thought processes, while assisting with the development of intuition about the class of problems for which it is applicable.

2. Analysis – is the study of anything complex by breaking the artifact into its component parts and then studying those parts and their interrelationships. Effort flow analysis promotes analysis through the product decomposition process that is integral to the method. Systems are decomposed into their component parts, and the interactions of those component parts are made apparent through operation and observation of the system in operation.
3. Abstraction – the process of generalization where the specific and the incidental are ignored; the concentration is focus on that which is general and essential. Effort flow analysis emphasizes the importance of the abstraction process in the use of effort flow diagrams as a mean of modeling the product without explicit knowledge of the system form. One of the great benefits of abstraction is the removal of inherent biases associated with particular solution forms, thus freeing the designer to pursue opportunities that are non-traditional or non-obvious when viewed in the context of the original artifact form.
4. Synthesis – the bringing together of separate forms and functions to create overall order. In the mechanical design domain the resulting order manifests itself in the form of artifacts that did not previously exist. Effort flow analysis is a synthesis process where product evolution concepts are synthesized from the abstract forms and relationships of the effort flow diagram through abstract new forms for component configurations that represent new and different solutions to existing problems.
5. Generally Applicable Methods – Pahl and Beitz suggest several methods to support systematic design work. These include the Method of Persistent Questions, the Method of Negation, the Method of Forward Steps, the Method of Backward Steps, the Method of Factorization, and the Method of Systematic Variation [49]. Of these methods, effort flow analysis supports the methods of Factorization and Systematic Variation. The Method of

Factorizations approach to problem solution takes the system and "factors" it into smaller sub-systems, which are more manageable. Effort flow analysis supports this approach in a product evolution context by identifying groups of components that are candidates for replacement with compliant mechanisms, allowing the designer to "factor" these component groups out of the system and focus on their redesign while leaving the interfacing components intact. Effort flow analysis also supports the Method of Systematic Variation in a product evolution context by allowing the designer to explore multiple design variants through the systematic generation of component combination permutations in effort flow diagrams where multiple contraction possibilities exist. Each unique opportunity is pursued to its reasonable end leading to multiple design variants each stemming from the same original arrangement of components.

6. Division of Labor and Collaboration – the complexity of designed systems has progressed over time to a point where an individual engineer is incapable of conceiving and understanding the system in its entirety. In fact, some have defined a complex system as one that cannot be fully comprehended by a single human [140]. For this reason, and others, the redesign activity is carried out by individuals from various disciplines, each individual working toward a common goal. This team of contributors must collaborate using a language that is common to all members to achieve the goal of the project. Effort flow analysis supports this collaboration by providing an abstract representation of the product that facilitates communication about the product, its components, and their interactions among the various disciplines involved in the design effort.

The correspondence of effort flow analysis with the framework from technical systems design is not accidental. One of the goals in developing the theory of effort flow analysis is to integrate the methodology with industrial practice. To achieve integration, the theory is developed such that it conforms to a standard framework that is widely recognized within the design community. As a theory, effort flow analysis can be classified based on the philosophical approach manifest in the theory.

6.2.2 - Normative Theory and Effort Flow Analysis

Effort flow analysis is a member of a class of design methods based on normative theory. Normative theories attempt to explain *the way things ought to be* (artifacts ought to be simple) based on a set of fundamental guiding principles. Contrast this with Descriptive theories, which attempt to explain *the way things are* (this artifact has a high quantity complexity). Directed product evolution is a normative process, the essence of which is perfectly captured by the TIPS principle of the Ideal System. The principle of the Ideal System says that a product will evolve to a state of ideality where the desired function is provided without consumption of any resources [4]. Clearly, this is statement of how things ought to be. The processes used to carry out the goals of normative design theories may be either prescriptive or descriptive in nature.

A prescriptive approach is one that is algorithmic or procedural, while a descriptive approach is cognitive or behavioral in nature [141]. Prescriptive design methods formulate designing as a technical rather than a ad hoc process; leading practitioners systematically down the redesign path toward the normative goals. It is the aim of prescriptive theories to generalize the various partial processes that may be applied to the redesign of a artifact to achieve an evolved product [141].

Effort flow analysis is a redesign methodology of the prescriptive type. The fundamental normative goal associated with effort flow analysis and its application to redesign is that products or systems can be driven toward ideality through the incorporation of compliant mechanism solutions for the provision of relative motion functionality.

As a prescriptive methodology, effort flow analysis relies heavily on the tenets of artifact theory to support the capture and storage of design knowledge. Knowledge related to *artifacts* (also referred to as technical systems or products) represents a specific subset of design knowledge. Looking back to a long history, the research into artifacts intends to understand the rules, forms and relations of processing substance, energy and information in designs [142]. In close relationship with the technical sciences, it studies physical, functional, morphological, structural, behavioral, realization and use aspects. One of the conclusions of artifact theory is that all design is in fact redesign. This argument is supported by the observation that although new artifacts are created, their

creation is made possible through the reuse of previously captured and stored knowledge [121].

When viewed in the light of artifact theory, the essence of the design process is captured by Newton's modest statement about his successes: "If I have seen further, it is by standing on the shoulders of giants." The creative process of design stands on the shoulders of the knowledge captured through the process of product evolution. The shoulders of giants allow us to see further down the path toward the future of a product, and that view is further focused using specific methodologies such as effort flow analysis.

6.3 - THE FINAL VERSION - EFFORT FLOW ANALYSIS

Effort flow analysis is now developed to a point where a practitioner's version of the method can be presented. The practitioner's version is built on the fundamentals that are presented in the previous chapters, but is free of the need for detailed explanations for each step. At this point, it is assumed that the fundamentals are sufficiently understood to allow a practicing engineer to apply the methodology to real products to produce real advancement in the evolution that product. The applicability of the effort flow analysis methodology is based on a set of fundamental propositions.

6.3.1 - The Propositions

<u>Proposition 5.1:</u> Application of effort flow analysis will lead to recurring component combinations that successfully incorporate both rigid body and compliant mechanisms to further product evolution.

<u>Proposition 5.2:</u> Application of the effort flow analysis methodology will lead to the creation of products that do not currently exist.

<u>Proposition 5.3:</u> Certain arrangements of mechanical transmitter components will repeatedly lead to successful evolutionary redesign concepts.

<u>Proposition 5.4:</u> In the absence of insurmountable functional or material conflicts, components joined at an interface where relative motion exists can be combined into a compliant structure.

These propositions summarize the collected intent of the work done to develop effort flow analysis as a comprehensive methodology for product evolution. These

propositions are embodied in the effort flow analysis process detailed in the following section.

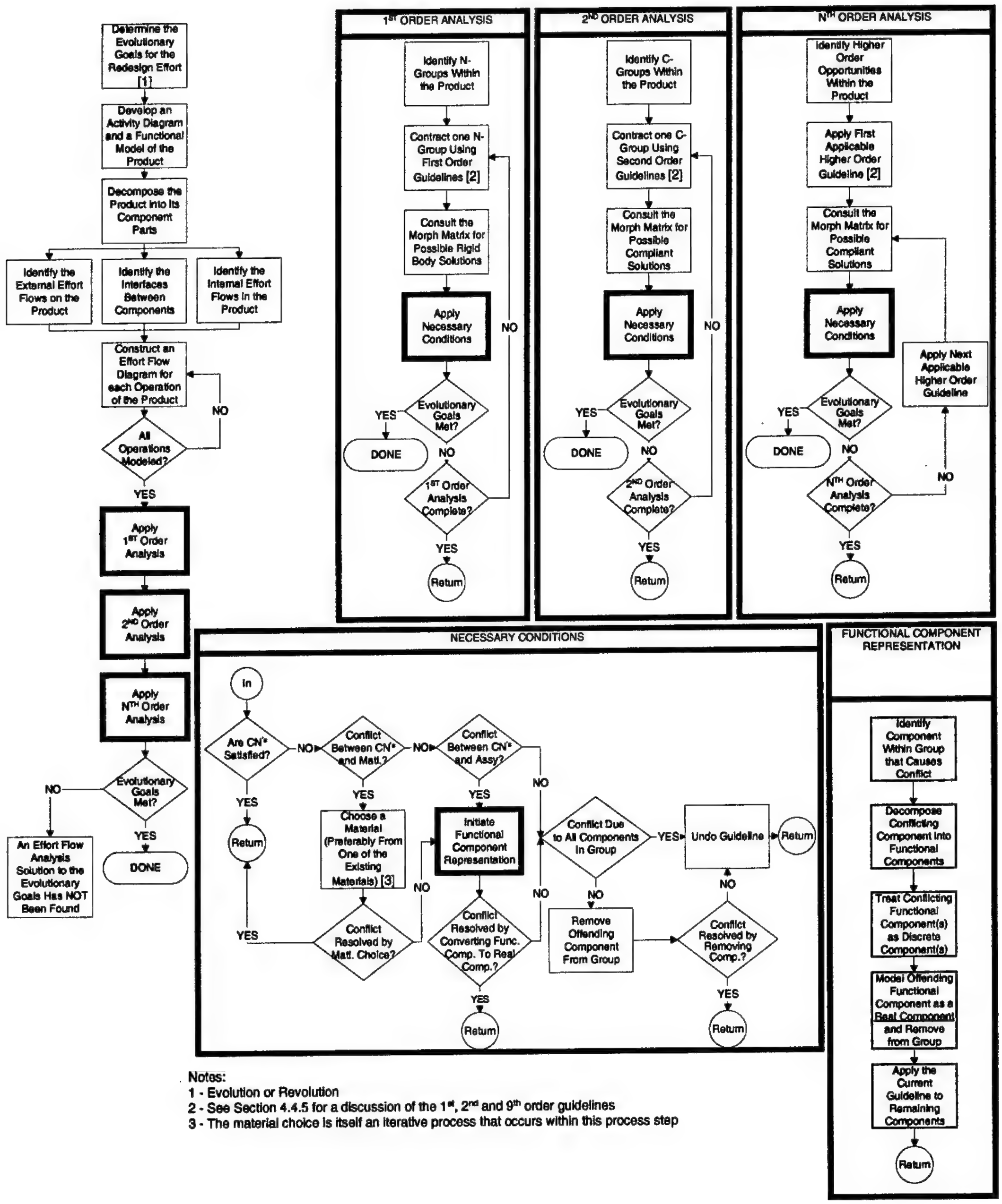
6.3.2 - Overview of the Practitioner's Version

The motivation for a practitioner's version of effort flow analysis comes from the observation that there is a disconnect between the results that come from design theory research and the needs of industry. Several authors have noted the fact that business conditions lead industry designers to apply pragmatic steps that are more closely aligned with specific product domains [141, 143, 144]. These pragmatic approaches are generally incompatible with the domain-independent methods that result from design methodology research. According to Frost [145], design practitioners often follow approaches that are similar to those coming from design methodology research; however, in the design approach taken in industry such similarity is concealed. A methodologist tends to evaluate the activity of the practitioner as an incomplete usage or even a trivialization of the perfect method. Hence, this difference in perspective produces the need to bring the design science methodologies and real design together. The effect of bringing research and practice together is to pitch effort flow analysis in a more applied format that can be explained in a brief session, and applied on the "back of an envelope." The following sections bring the practitioner's version of effort flow analysis toward that end.

The simplification process applied to the methodology does not change the big picture view of effort flow analysis; the overall process first presented in Chapter 4 is presented again here in the process flow chart of Figure 4.9. What is changed is the way the steps of the process are presented. The approach taken with the practitioner's version is to provide a high level overview of each step in the method. This high level approach is taken based on the assumption that the user has a working understanding of the fundamentals, the theory, and the philosophy of effort flow analysis as well as an intimate understanding of the artifact being redesigned. For cases where these assumptions are unsupported, then a reversion to the fully detailed presentation from Chapter 4 is needed.

Following the theme for the high level treatment of the steps of the process, the guidelines are presented in a condensed format as well. The guidelines are sorted and

categorized hierarchically; the organization is based on the type of link and the likelihood of achieving a successful component combination. Finally, a set of example solutions is presented where each example is correlated to the guideline that led to its instantiation. These solution modules are limited to those guidelines that lend themselves directly to the embodiment of specific solutions. The format of the example solutions provides the initial product, the effort flow diagram for the original product, the final product, and the effort flow diagram for the final product.



Notes:
1 - Evolution or Revolution
2 - See Section 4.4.5 for a discussion of the 1st, 2nd and 9th order guidelines
3 - The material choice is itself an iterative process that occurs within this process step

Figure 6.1: Effort Flow Analysis Flow Chart

6.3.3 - The Process Steps for the Practitioner's Version of Effort Flow Analysis

As before, the method follows the overall redesign methodology steps where the artifact being redesigned is observed, disassembled, analyzed, tested, 'experienced', and documented. The process is broken down into three phases, the Goals Phase, the Modeling Phase, and the Decomposition and Redesign Phase.

<u>GOALS PHASE</u>

STEP 1: Determine the overall goal for the redesign effort.

<u>MODELING PHASE</u>

STEP 2: Identify the operations performed by the system.

STEP 3: Identify the effort flows (external and internal) associated with each operation of the system.

STEP 4: For each operation, use an effort flow diagram to map the effort flow path beginning with the external source(s), continuing through all components involved in the operation, and ending at either the ground link or the work piece.

STEP 5: Aggregate the separate effort flow diagrams into a single product model.

STEP 6: Characterize all links based on their relative motion classification ($\mathbf{N}_{1,2,..,n}$, $\mathbf{C}_{1,2,\ ..,n}$, $\mathbf{R}_{1,2,\ ..,n}$, or $\mathbf{I}_{1,2,\ ..,n}$.) and the operation for which they are active (1, 2, 3, …, n).

<u>DECOMPOSITION & REDESIGN PHASE</u>

STEP 7: Successively decompose the diagram into groups connected by:

- a. N-Links
- b. C-Links
- c. CN-Links
- d. R-Links
- e. RN-Links
- f. RC-Links
- g. RCN-Links
- h. Other

STEP 8: Deduce the sub-functions and affected customer needs for each group.

STEP 9: Develop creative conceptual designs by combining components in each group using the appropriate Relative Motion, Graph Structure, and Functional guidelines along with the Analysis and Necessary Conditions guidelines.

6.3.3.1 - Goals Phase

Understanding the goal of the redesign effort is absolutely necessary. The two possible goal classes for product evolution using effort flow analysis are either incremental *Evolution* or discontinuous *Revolution* of the product design. The implementation of effort flow analysis to the product will depend on the answer to the goal question.

For an evolutionary goal, application of effort flow analysis is unchanged. For a revolutionary goal, product decomposition and modeling is taken to the lowest possible level. All multifunctional components are completely decomposed using the functional components approach. Once that product is fully decomposed, the overall effort flow analysis methodology is applied to the product model treating the functional components as if they were physical components of the product having the interface interactions associated with their behaviors and roles as function carrier. Once the goal of the product evolution effort is understood, product modeling and decomposition begins. The process steps for the Modeling and Decomposition & Redesign phases are presented in the next section. The process steps are condensed to brief statements of the action to be taken. The paragraphs that follow the process contain insights gained from the empirical study and from applying effort flow analysis to other products.

6.3.3.2 - Modeling Phase – Develop Activity Diagram & Functional Model

The first step in developing an activity diagram is experiencing the product. Experiencing the product means becoming intimately knowledgeable about its operation, its form, its shortcomings and its strengths. Use the product in its expected environment, use it for alternate purposes that are outside its expected environment, and observe your customers using the product. Only once an intimate understanding of the operation of the artifact is gained should the process of directed product evolution begin. Taking the knowledge gained from experiencing the product, develop an activity diagram that captures the operations of the product where improvements in performance are desired. Identification of the operations where product improvements are desired will depend on how well the functions of the product are understood.

The one functional modeling effort that absolutely must be done is to understand the needs of the customer (CN's). Redesign without the targets provided by the CN's is a waste of resources, as it may be impossible to determine whether the redesigned product has satisfied the customer needs or created previously nonexistent conflicts between the product and the expectations of the customer. The higher the fidelity of the customer needs data, the higher the fidelity of the conflict resolution methodology contained in the necessary conditions algorithm of effort flow analysis, and the higher the likelihood of a successful redesign effort. Once the CN's are understood, the product functional model can be evaluated.

Ideally, a full-scale functional model for the product is on hand from the initial product design effort. In which case, a reevaluation of the model should be sufficient to verify the continued applicability of the model. If no functional model is available, then it is incumbent on the designer to develop a model that captures the essence of the product functionality. Not only will this aid in the current effort, it will also add to the captured design knowledge for the artifact and aid future evolutionary efforts.

6.3.3.3 - Modeling Phase – Disassemble the Product

Product disassembly can occur during the phase where the artifact is being experienced, or it can be delayed until a deeper understanding of the overall product and its gross behavior gained. One advantage of not disassembling the product prior to operating and experiencing it is that biases toward the existing solution are kept at bay. The advantage here is that by delaying disassembly, the designer can avoid becoming enamored with a particular solution, and remain open to creative thought that is unencumbered by the influences of the legacy solution [1].

Once disassembly begins, it may be taken to any level desired, but should be complete enough to allow unhindered access to the components involved with providing the functions and operations that are the focus of the evolutionary effort. One technique that is beneficial to understanding the interactions between components is to apply the Subtract and Operate method (SOP) [1, 62] to gain an understanding of the behaviors associated with each component of the product. SOP systematically removes each component in the product and determines the effect that removal has on the overall

function of the product by operating the product without the component in place. The benefit of SOP in effort flow analysis is that the nature of component interactions can be determined by what happens to other components when one component is not in the product. Alternatively, the disassembly process may proceed by removing components while simultaneously operating a fully assembled version of the product. The bottom line in this step is to fully understand each component and its interaction with all components connect with it.

6.3.3.4 - Modeling Phase – Identify the Interfaces, Components, and Flows

As product disassembly progresses, the interfaces between components are identified, the components are named and characterized in a document similar to a bill of materials. The most important piece of information collected during this phase of the process is the data on the nature of the interactions at the interfaces. The accuracy of the relative motion characterization for the interfaces depends completely on the accuracy of the data collected here. With this need for accuracy in mind, the product should be operated to the extent possible throughout the disassembly process. Here again, operation of a fully assembled product will aid in identifying and understanding the interactions taking place between components.

The interactions of interest are those where forces and moments are transmitted between components. Here the artifact is operated to replicate, as closely as possible, the intended operational environment. The first types of effort flows that must be identified are those originating outside the system boundary of the product. These are the human inputs, other mechanical inputs, the ground links, the workpiece interactions, and the external reactions.

A note of caution is in order with regard to the human interactions. Humans are notorious for using products in ways never intended. For systems where the human interface is present, care should be taken to model as many human interfaces as can reasonably be expected. By accounting for the variations in human inputs, it should be possible to create preferred effort flow paths and design in human-factors features that encourage the use of those interfaces.

Once the external flows are identified and recorded, the resulting internal flows are determined. The accuracy with which the internal flows are identified depends on how accurately the component interfaces are identified. These steps are carried out simultaneously and continuously during the disassembly process. Where possible, physical modules are removed from the product as a whole.

> Definition: Physical Module, two or more connected components that can be separately assembled or removed in whole from an artifact while remaining in a stable connected state. Stability implies that external effort is not required to maintain the connectedness of the components.

Once removed, these modules can be evaluated separately as though they are separate artifacts unto themselves. The key pieces of information with a subassembly are its interfaces with the parent assembly. These interfaces will dictate the architecture of the evolved subassembly should it be identified as a candidate for component combination.

6.3.3.5 - Modeling Phase – Effort Flow Diagrams

In practice, creation of the effort flow diagram begins concurrently with identification of components, interfaces, and effort flows described above. A good practice is to mimic the layout of the components in the product in the layout of the nodes of the diagram. As the components are identified, place them in the diagram to form the nodes of the network. As disassembly proceeds, the interfaces are identified and the links are placed between the components to complete the network representation of the product. The node and link type definitions presented in Chapter 4 are reproduced here in Table 4.4, Table 6.2, and Table 4.3.

Table 6.1: Effort Flow Diagram Node Nomenclature

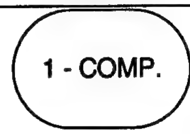
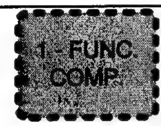
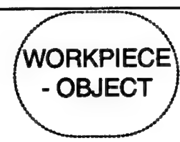
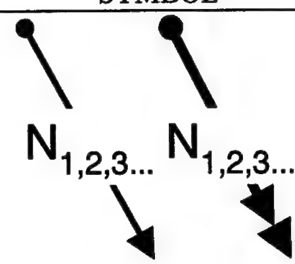
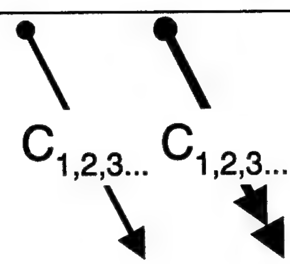
NODES		
ENTITY	SYMBOL	DESCRIPTION
Component		COMP. = Component Name 1, 2, 3,… = Component Number
Functional Component		FUNC COMP = Name of Function Provided by Feature of Parent Component 1, 2, 3,… = Number of Parent Component
Workpiece Object		WORKPIECE = External Object Operated on by the System OBJECT = Name of External Object

Table 6.2: Effort Flow Diagram Internal Link Nomenclature

INTERNAL LINKS		
ENTITY	SYMBOL	BRIEF DESCRIPTION
N-Link		N = No Relative Motion 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
C-Link		C = Component Relative Motion 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque

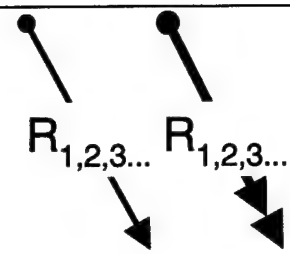
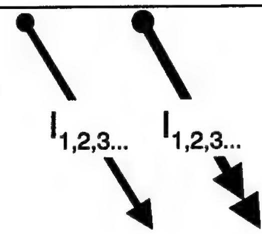
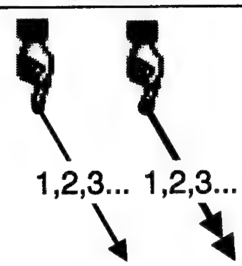
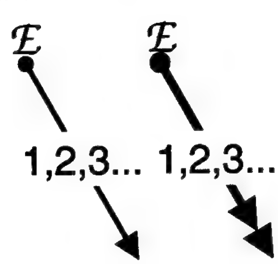
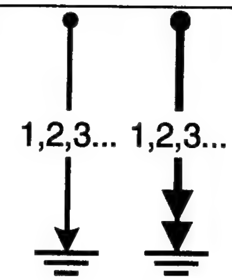
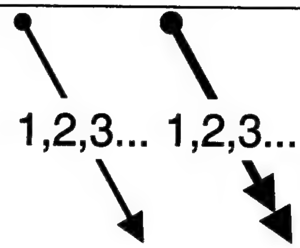
R-Link	 $R_{1,2,3...}$ $R_{1,2,3...}$	R = General Relative Motion 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
I-Link	 $I_{1,2,3...}$ $I_{1,2,3...}$	I = Interface Relative Motion 1,2,3,… = Operation Number Sign of 1,2,3… = Flow Direction relative to arrow. Single Arrow Head = Force

Table 6.3: Effort Flow Diagram External Link Nomenclature

EXTERNAL LINKS		
ENTITY	SYMBOL	BRIEF DESCRIPTION
Human External Effort	 1,2,3... 1,2,3...	Hand = Human Effort 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
General External Effort	 $\mathcal{E}$ $\mathcal{E}$ 1,2,3... 1,2,3...	$\mathcal{E}$ = External Effort 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque

Ground Link		SYSTEM TO GROUND LINK 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque
Workpiece Link		SYSTEM TO WORKPIECE LINK 1,2,3,… = Operation Number Sign of 1,2,3,… = Flow Direction relative to arrow. Single Arrow Head = Force Double Arrow Head = Torque

Constructing an effort flow diagram typically progresses one product operation at a time. For each operation, a fully assembled product or subassembly is operated while a disassembled version is observed and manipulated to determine the nature of the interactions occurring across the component interfaces. This two-pronged approach allows the designer to see the gross motion of the components in the operational product while at the same time gaining insights from manipulation of the individual components. As each operation is carried out, the effort flow diagram is populated by characterizing the links based on the observed relative motion between components.

Because effort flow analysis is a high level approach to product modeling, it is inappropriate to generate a detailed analysis of forces and moments while creating the effort flow diagram. Resources are conserved by waiting until groups of components are identified for combination before carrying out in-depth analysis of any component. A more appropriate focus in the diagram generation phase is ensuring the correct characterization of relative motion at the interfaces is achieved. Focusing on correctly identifying and characterizing the interfaces leads directly to higher confidence in the component combination opportunities that arise. It should be noted that considerable latitude exists for the designer to make modeling decisions regarding interface characterization.

There are two components necessary for an interface to be identified as active during an operation, the presence of an effort flow and one of the four classes of relative motion. The designer has the duty to decide which interfaces are included and which are not included in the product model. A consistent benchmark for making this decision is necessary to ensure that relevant interfaces are not overlooked and that inconsequential interfaces are not included. The specifics of a benchmark will certainly be artifact class specific, but some general guidance is given here.

1. Include an interface characterization in the model if its exclusion would prevent an effort flow path from terminating at an external reaction.
2. Include an interface characterization in the model if its exclusion would negate the effect of an entire operation.
3. Exclude an interface characterization from the model if the effort flow at the interface not essential to operation of the product, for example when an effort flow path exists that is not in the primary flow path for the operation, it can be excluded from the model.
4. Exclude an interface characterization when no product function can be associated with effort flow across the interface for the operation under consideration. This does not imply that an interface should be physically removed if no effort flow occurs for the operations modeled unless all operations of the product are modeled. This is an opportunity to apply the SOP methodology to determine the need for the components connected across the interface.

Once the interfaces are characterized for all product operations and a final check of the model is accomplished to ensure that all operations and interactions have are modeled, the analysis process begins.

6.3.3.6 - Decomposition & Redesign Phase – Analysis Leading to Application of the Product Evolution Guidelines

Analysis of the effort flow diagram just developed relies on the designer's ability to recognize or deduce patterns in the structure of the graph. The goal of effort flow analysis is to identify the structures in the diagram where known product evolution

opportunities exist. The strategy is to systematically isolate or factor the diagram into these known structures using the interface characterization done during the modeling phase.

Factorization begins with identification of component groups where all the nodes are connected by the same link type, these groups of components are then evaluated for combination using the product evolution design guidelines. The process progresses to include groups of components connected by mixed link types and finally to instances of components connected in specific arrangements such as parallel structures. Once the diagram is factored into known structures, the guideline corresponding to that structure is sought out and applied. In each case, one or more members of the set of global guidelines are applied to the result to ensure that the resulting design variant is indeed feasible. The global guidelines play a role in determining the combinability of any proposed evolution of the product.

In cases where more than one guideline appears to apply, an evaluation of the results for each guideline is needed. Utility theory provides an appropriate framework for evaluating the results of the competing guidelines. The utilitarian measure of "providing the greatest good" is used to determine which guideline path to choose. After the competing guidelines are applied and their utility is measured, the design variant with the greatest utility is chosen and checked against the necessary conditions. If the combination cannot be made to work, the guideline with the next highest utility is applied and the process of checking the necessary conditions is repeated until a solution is found, or until no solution is found and the opportunity is discounted as infeasible.

6.3.3.7 - Decomposition & Redesign Phase – Design Guidelines

The hierarchical order of analysis carried out on the product model is based on a guideline classification scheme used in effort flow analysis. The approach taken is to assign classes to the guidelines based on the likelihood of achieving a successful component combination that guideline. The nomenclature used is: 1^{st}-order, 2^{nd}-order, N^{th}-order and global, with the 1^{st} order guidelines being the most likely, and higher order guidelines being less likely. The exception to this is the set of global guidelines, which are broadly applicable recommendations that ensure the success for all classes of

guidelines. The 1st-order guidelines are N-Link based, the 2nd-order guidelines are C-Link based, and the Nth-order guidelines are based on R-Links or various combinations of the link types.

The 1st, 2nd, Nth-order classification scheme is unrelated to the 4-star guideline support entry associated with each of the derived guidelines. The 4-star system is developed in the *Guideline Extraction and Generation* section of Chapter 4, where the stars correspond to the degree of empirical support found for a guideline during the conduct of the empirical study. The guideline classes are developed in the *Product Evolution Design Guidelines* section of Chapter 3, where the classes correspond to the likelihood of achieving a successful component combination. Although there may be a correlation between these two systems, the analysis has not been done and hence cannot be claimed.

Table 6.4: Product Evolution Design Guideline Domains

Domain	**Class**
Relative Motion Domain	
N-Link	*1st*
C-Link	*2nd*
R-Link	*Nth*
Mixed	*2nd or Nth*
Graph Structure Domain	
Parallel	*Nth*
Serial	*Nth*
Mixed	*Nth*
Function Domain	*Nth*
Analysis Domain	*Global*
Necessary Conditions Domain	*Global*

In order to make the effort flow analysis guidelines more accessible, they are further classified into a lexicon with the five broad domains shown in Table 6.4. The guideline domains are used as the overall guideline lexicon as a way to aid the designer in accessing the guideline that is most appropriate for a given situation. In this lexicon, the relative motion domain refers to the interface type addressed in the guideline. The graph structure domain refers to the arrangement of the links (N, C, R, I) and nodes in the effort flow diagram; this domain is analogous to the arrangement, for example, of resistors in an

electric circuit. Resistors can be in parallel, in series, or a mix of series and parallel elements. The function domain contains design guidelines that are related to the functionality of the combined components. The analysis domain contains design guidelines that are germane to the analysis of combined components in both rigid body and compliant mechanisms. The final domain contains a set of guidelines collectively known as the Necessary Conditions for successful component combination. The Necessary Conditions domain contains the guidelines associated with the functional and material requirements for component combination derived in the *Necessary Conditions for Successful Component Combination* section of Chapter 3. The results of applying the lexicon to the guidelines derived from the empirical study are shown in Table 6.5 through Table 6.9.

An interesting side note is that the 1st, 2nd, and Nth-order classes are subdivided by the four domains, indicating that the likelihood of success for guidelines in the Relative Motion Domain is higher than for guidelines in the Graph Structure and Function Domains.

Table 6.5: Relative Motion Domain Guidelines

RELATIVE MOTION DOMAIN	
1st-order guidelines	
N-GROUPS	
Recommendation	Combine groups of components connected only by N-Links into a single rigid component.
Guideline Support	****
2nd-order guidelines	
C-GROUPS	
Recommendation	Combine groups of components connected only by C-Links into a single compliant component.
Guideline Support	****

C-LINK WITH STRAIN ENERGY STORAGE	
Recommendation	Replace C-Links and components providing the "storage/supply energy" function with an integral compliant component that uses strain energy to satisfy the desired energy storage/supply function.
Guideline Support	***
CN-LINKS – COMPLIANT COMBINATION	
Recommendation	CN-Links behave primarily as C-Links; therefore, give higher priority to the contribution of the C-Link in determining a combined solution. CN-Groups are combinable using the C-Group Guideline approach provided the required constraint on the DOF needed for the N-Link is achieved.
Guideline Support	***
N^{th}-order guidelines	
1-DOF R-LINK	
Recommendation	Combine components connected by a 1-DOF joint using a compliant mechanism.
Guideline Support	****
RN-LINKS – COMPLIANT COMBINATION	
Recommendation	RN-Links behave primarily as R-Links; therefore, give higher priority to the contribution of the R-Link in determining a combined solution. RN-Groups are combinable using the guidelines that treat various instances of the R-Link while continuing to provide the constraint behavior provided by the N-Link.
Guideline Support	***
R-LINK SMALL MOTION	
Recommendation	Combine components connected by small motion R-Links to form a compliant mechanism.
Guideline Support	**
R-LINK LARGE MOTION	
Recommendation	Do not attempt to combine components connected by R-Links where the general relative motion is large and/or continuous except when all other options have been expended.
Guideline Support	* No product was observed to contradict this guideline, hence it is assumed to be valid.

R-LINK → C-LINK	
Recommendation	Replace a R-Link connecting rigid bodies with a C-Link connecting compliant bodies.
Guideline Support	**
R & C ACTIVE FOR SAME OPERATION	
Recommendation	An R-Link can initiate C-Link behavior in a component. Take care to recognize interfaces where the R & C Link characterizations occur, as the complexity of combination through such an interface will be made more complex due the motion.
Guideline Support	***

Table 6.6: Graph Structure Domain Guidelines

GRAPH STRUCTURE DOMAIN	
R-LINKS IN SERIES	
Recommendation	When R-links connecting multiple components have the same DOF (translation or rotation), then those components can be combined until an interface is reached where the required motions are for a different DOF.
Guideline Support	*
PARALLEL R-LINKS	
Recommendation	Parallel R-Links may be combinable under certain scenarios.
Guideline Support	**
R-LINK NETWORK	
Recommendation	A serial R-Link graph structure that is in parallel with another R-Link may lead to contraction of the serial portion of the graph structure if the relative motion at the common nodes can be maintained.
Guideline Support	**
1-DOF GROUNDED MECHANISMS	
Recommendation	A 1-DOF grounded mechanism may be designed as a compliant mechanism by making one or all of the links compliant.
Guideline Support	**

PARALLEL R & C LINK COMBINATION	
Recommendation	Combine parallel R-Links and C-Links by incorporating the Allow DOF function of the R-Link with the Store Energy function of the C-Link into a single compliant mechanism.
Guideline Support	**
REDUNDANT PARALLEL LINKS	
Recommendation	Remove non-relevant parallel links from models undergoing component combination.
Guideline Support	**
CR-LINKS	
Recommendation	When an interface consists of an R-Link and a C-Link, the two relative motions generally act in orthogonal directions; hence, combination is unlikely due to the more complex motion at the interface.
Guideline Support	**

Table 6.7: Function Domain Guidelines

FUNCTION DOMAIN	
Global Class	
FUNCTIONAL COMPONENTS	
Recommendation	Decompose multi-functional components into virtual links and nodes representing the individual interfaces and features of the component used to provide the functions of the original component.
Guideline Support	**
REDUCE THE NUMBER OF DOF USED TO PROVIDE A FUNCTION	
Recommendation	Minimize the number of R-Links used to provide a given function or set of functions – move toward direct actuation between the effort source and the workpiece.
Guideline Support	**
INTEGRAL ATTACHMENT	
Recommendation	Use integral attachment mechanisms to replace traditional fasteners.
Guideline Support	***

Table 6.8: Analysis Domain Guidelines

ANALYSIS DOMAIN	
Global Class	
TIME DEPENDENT BEHAVIOR IN COMPLIANT POLYMERS	
Recommendation	Avoid the use of polymer compliant mechanisms in applications where the mechanism is subject to sustained loads or deformations.
Guideline Support	***
CHOOSING BETWEEN CONTRACTION OPTIONS	
Recommendation	When a graph structure provides more than one choice for graph contraction, choose the contraction that leads to the fewest number of remaining inter-node links.
Guideline Support	**
DISTRIBUTION OF COMPLIANCE	
Recommendation	Determine whether the embodied compliant mechanism should use a LOCALIZED or a DISTRIBUTED architecture for the compliant region.
Guideline Support	****
DISTRIBUTED COMPLIANCE	
Recommendation	Compliant solution architectures dictating that broad regions of a device be compliant are classified as distributed compliance problems.
Guideline Support	***
LOCALIZED COMPLIANCE	
Recommendation	Compliant solution architectures dictating that the small regions of the device be compliant are classified as Localized Compliance problems.
Guideline Support	**
I vs. BENDING STRESS	
Recommendation	When a bending deflection is specified, reduce the second moment of area to reduce the stress and thus the likelihood of fatigue failure in a compliant mechanism.
Guideline Support	***

LENGTH vs. BENDING STRESS	
Recommendation	When a bending deflection is specified, increase the length over which the deflection is distributed to reduce the maximum stress and thus the likelihood of fatigue failure in a compliant mechanism.
Guideline Support	**

Table 6.9: Necessary Conditions Domain Guidelines

NECESSARY CONDITIONS DOMAIN	
Global Class	
NECESSARY CONDITIONS	
Recommendation	The necessary conditions for component combination must be satisfied for any proposed component combination opportunity.
Guideline Support	****
MATERIAL SELECTION	
Recommendation	Identify one of the existing materials from the components being combined as a first candidate for use in the combined component.
Guideline Support	****

6.3.4 - Solution Modules

One of the strengths of effort flow analysis is the ability to use the method as a concept generation engine. Effort flow analysis is especially useful in a design-by-analogy environment because of the captured design knowledge pertaining to compliant mechanism problems and their solution. This design knowledge comes from each of the product evolution guidelines in Table 6.5 through Table 6.9, which resulted from observed compliant mechanism implementations in one or more consumer products.

These compliant mechanism implementations are captured in Table 6.10 through Table 6.13. The organization of the tables uses the same lexical scheme as the design guidelines. This organization allows the designer to use the captured solution modules in a design-by-analogy context to assist in the generation of creative and innovative solutions to problems involving any artifact class in the mechanical domain.

In design-by-analogy, knowledge is retrieved from a familiar situation that is similar to the current situation, that knowledge is transferred to the current situation to solve the problem at hand. One of the key enablers of design-by-analogy is the use of a common abstraction to represent design knowledge across domains [146]. The semantic network representation used in the effort flow diagram is just such an abstraction. The strength of this representation is that any component and its mechanical interactions with neighboring components can be modeled with the effort flow diagram. Hence, the knowledge captured in the design guidelines and solution modules can be transported across product domains to provide the spark of creativity and innovation needed to solve a broader variety of problems. This transportability has the potential to leverage a single solution observed in the original product from a single product domain to multiple solutions in multiple domains.

The approach taken in effort flow analysis is to apply the methodology to the product of interest in the manner described in the previous section. When an appropriate design guideline is identified, the designer accesses the solution-modules table for the solution example corresponding to the guideline in use. The table contains as a minimum the references to the empirical study results contained in Appendix B as well as any pertinent references from the technical literature where either background information or further solution modules can be found. Some of the entries also contain the original and evolved effort flow diagram structure along with a schematic of the original and evolved product or products associated with the guideline. The results are presented in Table 6.10, where some of the guidelines are excluded from the tables, as they do not correspond to any particular type or form of solution.

Table 6.10: Relative Motion Domain Solution Modules

RELATIVE MOTION DOMAIN	
N-GROUPS	
Supplemental material	Solution Examples: Tool-Case, Compliars, Ice Cream Scoop, Wire Strippers, Tool Holder, Bicycle Frame, Forceps, Staple Remover
References	[1, 3, 6, 7, 12, 46, 63]
C-GROUPS	
Supplemental	Solution Examples:

material	Clip Spring to Cylinder in the pens Serotta Colorado → Ibis Silk Ti Bicycle Frames Compliant Ice Cream Scoop → Zerol Scoop
References	[129]
C-LINK WITH STRAIN ENERGY STORAGE	
Supplemental material	Solution Examples: Kitchen clip product where the spring is replaced by the bending beam in the one-piece product. Bicycle suspensions where the coil spring of the multi-link suspension is replaced by the leaf spring/chain stay Stainless Ice Cream Scoop → Zerol Scoop & Compliant Version
References	[129]
CN-LINKS – COMPLIANT COMBINATION	
Supplemental material	Solution Examples: Pens, Ice Cream Scoop, Kitchen Clip, Wire Stripper, Tool Case, Clothes Hanger, Clothes Pin, Compliars, Forceps, Staple Rem. This guideline is demonstrated by combination of the arms and spring, which produces the beams, hinge and latch in the evolved product in Figure 6.2 below. The DOF constraint is changed from resisting a compressive load in the original hinge to resisting a tensile load in the evolved hinge. In addition, the on out-of-plane motion constraint at the interface between the arms of the original product is enforced by the hinge and latch of the evolved product.

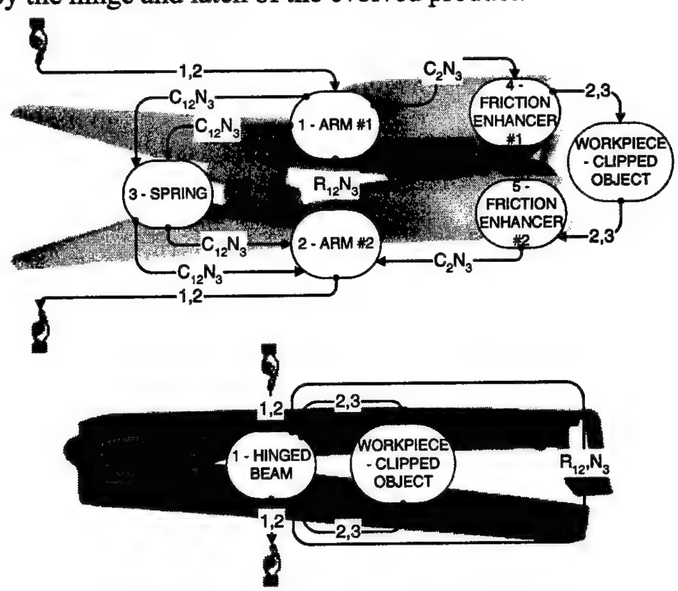
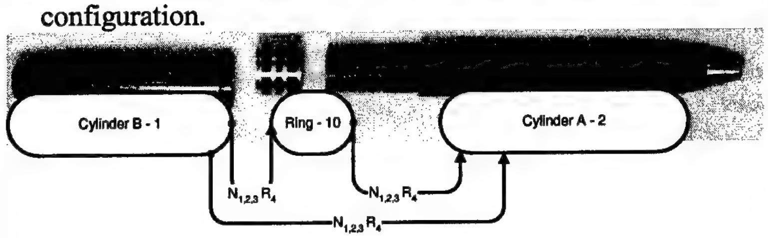


Figure 6.2: CN-Group Structure in Graph

References	[132, 147-158]
1-DOF R-LINK	
Supplemental material	Solution Examples: Toolcase Hinges, Kitchen Clip, Tool Holder, CD Case, Bicycle Frame
References	[29, 129]
RN-LINKS – COMPLIANT COMBINATION	
Supplemental material	Solution Examples: Pens, Ice Cream Scoops, Kitchen Clip, Wire Stripper, Tool Case, Tool Holder, Compliars, Forceps, Staple Remover
References	[29, 129]
R-LINK SMALL MOTION	
Supplemental material	Solution Examples: Ice Cream Scoop, Wire Stripper, 4-Bar Bicycle Frame, Clothes Hanger, Compliars, Forceps, Staple Remover
References	[6, 129, 132]
R-LINK LARGE MOTION	
Supplemental material	Assembly hinges, "twist ties" or variants thereof, rivets, press in plastic fasteners
References	[132]
R-LINK → C-LINK	
Supplemental material	Bicycle Frames, Ice Cream Scoop, Bicycle Brake, Wire Strippers, Tool Case, Staple Remover
References	[130]
R & C ACTIVE FOR SAME OPERATION	
Supplemental material	Solution Examples
References	

Table 6.11: Graph Structure Domain Solution Modules

GRAPH STRUCTURE DOMAIN	
R-LINKS IN SERIES	
Supplemental material	Solution Examples: Tool Case, Swing Arm Bicycle Frame, Compliars, Forceps
References	[29, 130]
PARALLEL R-LINKS	
Supplemental material	Parallel links may represent networks of independent DOF, or they may represent redundant interfaces in initial models or models undergoing evolution. Nearly infinite permutations exist for parallel graph structures; for example, see An Atlas of Graphs [159]. Solution Examples: Kitchen Clip, Tool Case, Clothes Pin, Clothes Hanger, Ice

	Cream Scoop
References	[159]
R-LINK NETWORK	
Supplemental material	Solution Examples: Pens, The rationale behind the statement about the DOF between the components in the network is based on the absence of interfaces with nodes outside the network of three node and associated R-Links. To accomplish this contraction in the SKILCRAFT pen, Figure 6.3, choose one of the R-Links adjacent to the Ring, and move it to the other side of the Ring. This results in only N-Links on the path where the R-Link was removed, and N-Links can be combined if not prevented by material or assembly constraints. The resulting R-Link must now provide the same number of DOF as the original series configuration.  Figure 6.3: Original R-Link Network in Skilcraft Pen  Figure 6.4: Original Nut, Washers & Bolt Assy.

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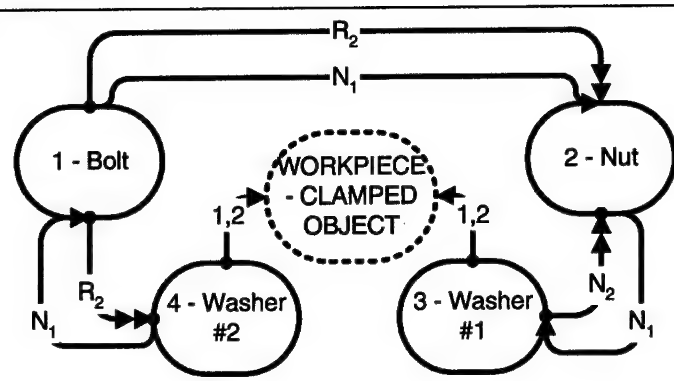

Figure 6.5: Original R-Link Network for Nut, Washers & Bolt Assy.

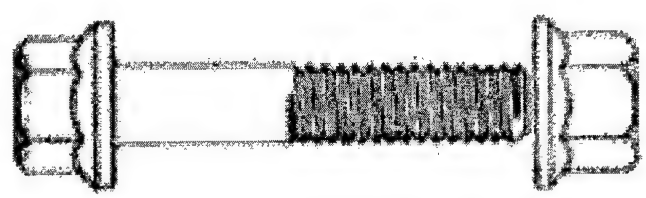

Figure 6.6: Evolved R-Link Network in Nut and Bolt
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<tr>
<td>References</td>
<td>[99]</td>
</tr>
<tr>
<td colspan="2">1-DOF GROUNDED MECHANISMS</td>
</tr>
<tr>
<td>Supplemental material</td>
<td>
Solution Examples:

4-Bar Bicycle Frame, Bicycle Brake.

Figure 6.7 below models a 4-Bar mechanism used in the original bicycle brake product. The spring stores energy relative to ground. Based on this guideline, the Ground Link and at least one of the connected members could be combined into a compliant member to produce the spring behavior.

In the bicycle brake, a fully compliant mechanism is not achieved in the evolved product, due mainly to combined loading from braking forces. Hence, three possibilities remain: combine any three adjacent members into a compliant mechanism. The possibilities are; Arm-Pad Mount-Link; Link-Ground-Arm; or Pad Mount-Link-Ground. In either case, the attaching joints would be absorbed into the mechanism through the N-Links.
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</table>

Looking at the original mechanism, a relatively clear choice presents itself in the form of the Link. The Link is the most slender member of the original components, and thus lends itself most readily to conversion to a compliant member based on the I vs. BENDING STRESS guideline. The designer apparently chose to apply the Replace R-Links with C-Links approach rather than a full component combination of all three members, probably due to manufacturability. Additional rationale for the combination chosen comes from the direct functional conflict that arises when making the arm compliant. The arm must provide the Transmit Mechanical Energy function in the bending mode, which requires stiffness and conflicts with the need for compliance. Hence, the most logical choice is to select the option that makes the Link member compliant.

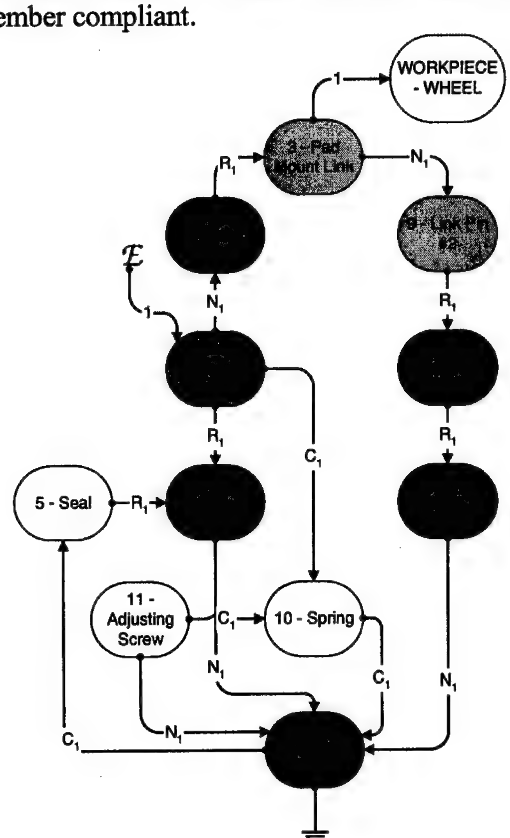


Figure 6.7: 4-Bar Mechanism as Shown in Effort Flow Diagram

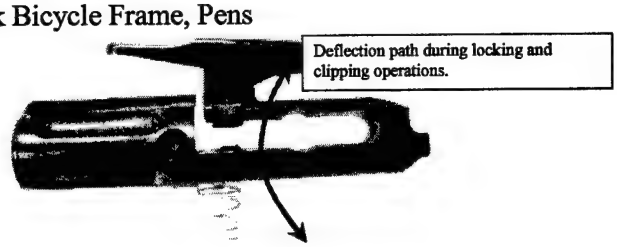
References	[29, 43, 130]
PARALLEL R & C LINK COMBINATION	
Supplemental	Solution Examples:

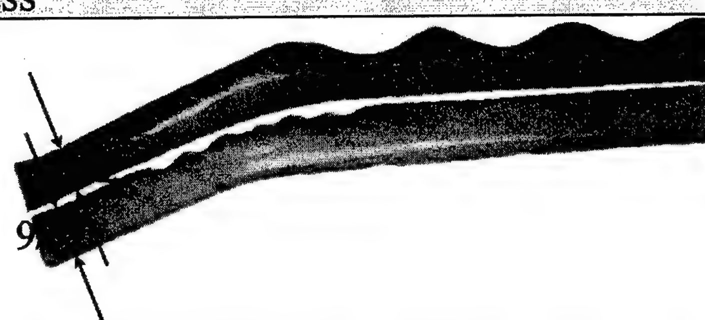
material	Kitchen Clip, Clothespin, and Ice Cream Scoop products
References	
REDUNDANT PARALLEL LINKS	
Supplemental material	Solution Examples Hinge Structures in Tool Case,
References	[159]

Table 6.12: Function Domain Solution Modules

FUNCTION DOMAIN	
FUNCTIONAL COMPONENTS	
Supplemental material	Components that serve more than one function can be separated into multiple, equivalent single-function components that can potentially afford combinations not previously feasible because of relaxation of material or other constraints for the single-function components.
References	[1, 83]
REDUCE THE NUMBER OF DOF USED TO PROVIDE A FUNCTION	
Supplemental material	Solution Examples Stainless Scoop to 4-Piece Scoop and ultimately to the 2-Piece Rigid Scoop
References	
INTEGRAL ATTACHMENT	
Supplemental material	Solution Examples
References	[132, 147-158]

Table 6.13: Analysis Domain Solution Modules

ANALYSIS DOMAIN	
TIME DEPENDENT BEHAVIOR IN COMPLIANT POLYMERS	
Supplemental material	Solution Examples: 4-Link Bicycle Frame, Pens  Figure 6.8: Augmented Compliant Polymer Mechanism For example, the compliant mechanism in the Clip Spring of the

	Pilot Explorer pen is augmented by a metallic coil spring in Figure 6.8 above. The purpose of the spring is deduced to be creep prevention. The compliant polymer device performs all required operations when the spring is removed, but inclusion of a temporal aspect to the performance evaluation may lead to non-performance due to the effect of creep.
References	[29, 129, 136, 137]
DISTRIBUTION OF COMPLIANCE	
Supplemental material	
References	[29, 41, 105]
DISTRIBUTED COMPLIANCE	
References	Continuum Model: [24, 36-41, 44, 45, 123-126] Pseudo-Rigid Body Model: [29-32, 34, 42, 43, 127-130] Bistable Mechanisms: [35, 131] Mechanical Advantage: [27]
LOCALIZED COMPLIANCE	
Supplemental material	Solution Examples: CD Case, Tool Case, Kitchen Clip, Bottle Cap, Wire Strippers, Clothes Hanger, Clothes Pin, Forceps,
References	Living Hinge, [29, 127, 132, 133] Assembly Hinge, [132] Passive Joints, [29] Q-Joints, [28] Cross Axis Flexural Pivots, [134] Torsional Hinges, [29] Split Tube Flexures [135]
I vs. BENDING STRESS	
Supplemental material	 Figure 6.9: Reduced Second Moment of Area in a Bending Beam
References	[29, 129]
LENGTH vs. BENDING STRESS	
Supplemental material	
References	[29, 129]

MATERIAL SELECTION	
Supplemental material	
References	[29, 104, 105, 115, 136, 160, 161]
References	[8]
CHOOSING BETWEEN CONTRACTION OPTIONS	
Supplemental material	Solution Examples: Tool Hanger, Tool Case, Bicycle Brake For example, combine components across the N-Links and C-Links shown in Figure 6.10below into a single "mega component" in variant #2 leaving the other components in their original state. Compare this choice to variant #1, which distributes the Spring and Hinge Pin combinations over the Base and Arm components respectively. Applying the "mega-component" approach results in a clearer picture of the connectivity between the nodes of the combined component and the remaining nodes. In addition, the combination of all the components into a single node implies that only one new component must be designed to mate with the remaining original interfaces that remain intact in the new design.

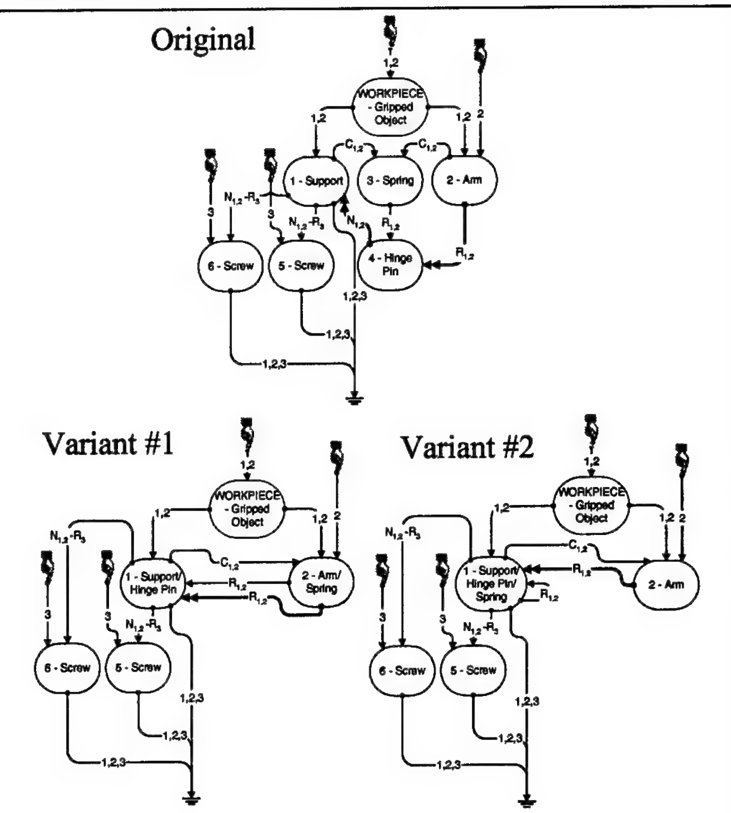


Figure 6.10: Example of Choosing a Combination Opportunity

6.4 - REPEATABILITY STUDY

It is proposed that effort flow analysis can be applied by engineers with varying backgrounds without significant differences in the results. In order to verify this proposition, a study is conducted to determine whether the results of applying effort flow analysis to the redesign of two products are reliable, repeatable, and accurate. The study is conducted using 17 subjects enrolled in the graduate course on mechanical design (ME 392M) at the University of Texas at Austin.

There are two aspects to the repeatability study. The first aspect is to establish the repeatability of creating an effort flow diagram for a product, and the second aspect is to establish the repeatability of reaching a known product evolution state through application of the methodology using only the three fundamental guidelines (N-Group, C-Group, and R-Links).

Verifying the repeatability of generating correct effort flow diagrams comes from a comparison of each subject's effort flow diagram to a known standard. Because effort flow diagrams are semantic networks, they are analyzable using tools from the graph theory. In this case, analyses of the study results are carried out by comparing the resulting effort flow diagrams to the expected diagram using an adjacency matrix.

The adjacency matrix represents the connectivity of the nodes and links in matrix form. The adjacency matrix represents all isomorphic graphs in exactly the same manner; hence, effort flow diagrams with identical connectivity relationships have identical adjacency matrices. Diagrams with variations in the connectivity will have different values in the corresponding entries of the matrix.

Each row and column of the matrix is associated with a component. The matrix is filled by placing a "1" in the column of each component that interfaces with the component in the current row. The diagonal of the matrix represents the connectivity of a component with itself; hence, these cells are used for supplemental information. In this case, the diagonal is used to indicate which components have external interfaces, and are populated by placing an "E" if the component has <u>any</u> external interfaces, and an "I" otherwise. External interfaces are interfaces with the environment where efforts enter or leave the system.

To facilitate the use of the adjacency matrix, the components of the product are pre-numbered. Pre-numbering helps to ensure that the rows and columns of the adjacency matrix represent the same component for each subject. The subjects construct the effort flow diagram using the predefined component numbers, and then apply the concepts of the effort flow analysis method to redesign the products.

The application of effort flow analysis concepts to the products of the study produces the second measurement of repeatability, and that measure is the number of components that remain in the redesigned product. In this work, the optimally redesigned product is the one that minimizes the number of parts in the product. This minimization can occur through component removal or through component combination. Analysis of the repeatability of arriving at the desired redesigned product requires a more subjective analysis of the resulting component composition in the product, and a modified adjacency matrix will be used to represent the evolved products.

The adjacency matrix for the redesigned product is constructed after the redesigned product is modeled using the effort flow diagram. This portion of the study tests the repeatability of design guideline application. The guidelines available to the subjects are limited in number, but broad in scope. The expectation is that there will be more variability in the resulting designs. No judgments are made about the appropriateness of the redesign results; the focus is on whether the expected components are identified for redesign and whether those components are then incorporated in the redesigned product.

6.4.1 - Products Used in the Study

In choosing a product for analysis, two conflicting considerations must be treated. First, because of the study participant's status as students, the product must be sufficiently simple to ensure that the analysis can be accomplished in a reasonable amount of time. Second, the product must be complex enough to test the repeatability of the method. An additional consideration is the learning curve associated with applying a methodology such as effort flow analysis. To lessen the effect of the learning curve, one product for the test is chosen for its simplicity, and the other is chosen to allow more freedom in application of the design guidelines. The final consideration is that the products must have a known product evolution state.

With these competing goals in mind, the two products chosen for the study are an eight component staple remover, and a nine component retractable ballpoint pen. The staple remover presents a product with relatively few components and clearly visible interfaces and component behaviors. The staple remover chosen for the study is the Office Max® pinch type staple remover (Figure 6.11), which represents a product that has proven to be evolvable to either a five-piece compliant configuration developed in the MADLab (Figure 6.12), or to the two-piece rigid configuration of the BOSTICH® staple remover (Figure 6.13).

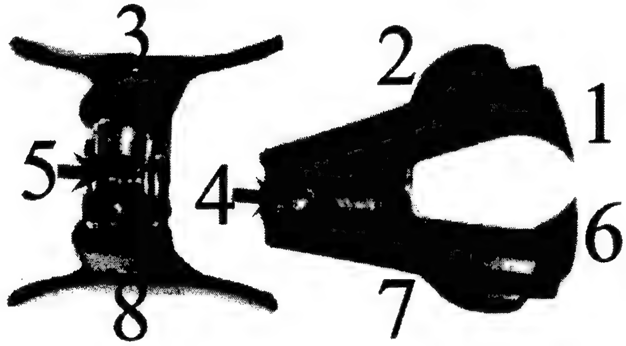


Figure 6.11: Staple Remover Labeled Schematic

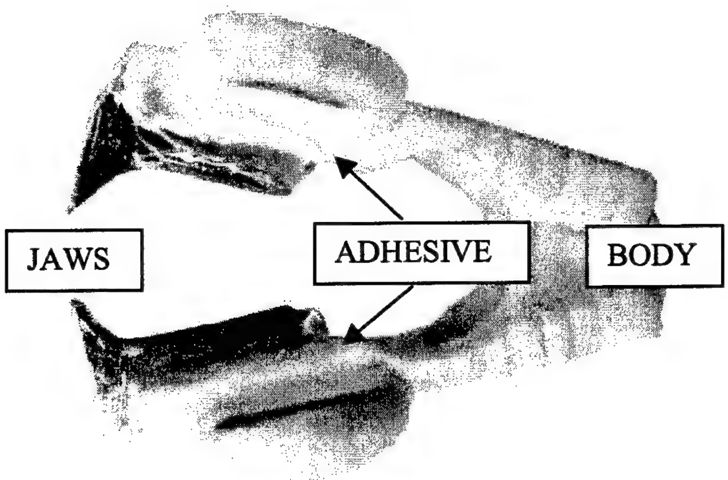


Figure 6.12: MADLab Compliant Staple Remover

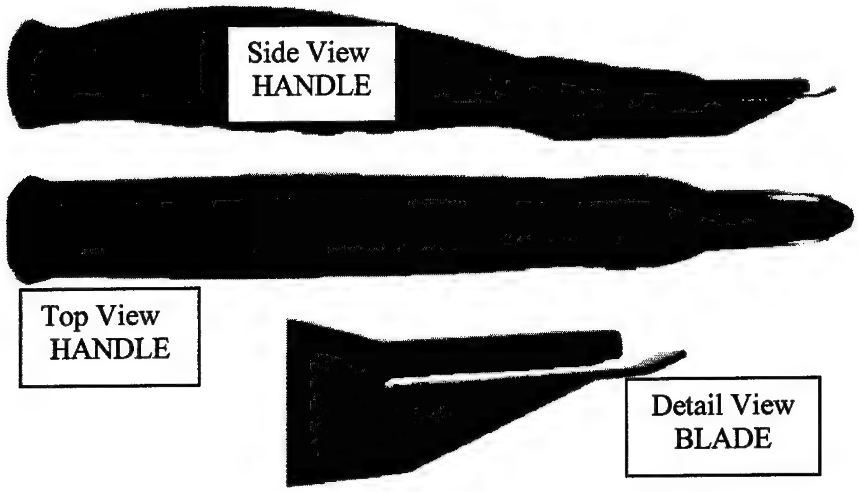


Figure 6.13: BOSTICH® 2-Piece Staple Remover Rigid)

The ballpoint pen, on the other hand, represents a product that embodies multiple functions satisfied using multiple components and subassemblies. The interfaces in the pen are not obvious with out complete disassembly, and the interactions during operation are not completely obvious. The pen chosen for the study is the Bic® Clear Clics ™ retractable ballpoint pen (Figure 6.14), which represents a product that is evolvable to several known configurations, one of which is shown in Figure 6.15. In addition, the pen uses all the know link types (NCR) in its operations, some of which are used in rather subtle ways. These subtleties allow for a more in depth analysis of the consistency of effort flow diagram construction with a relatively simple product. Finally, the presence of the N, C, and R links leads to the testing of the repeatability of product evolution using all three of the fundamental guidelines.

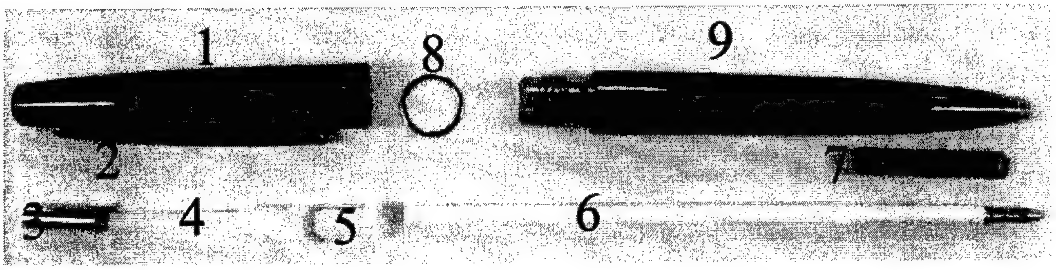


Figure 6.14: Bic® Pen Labeled Schematic

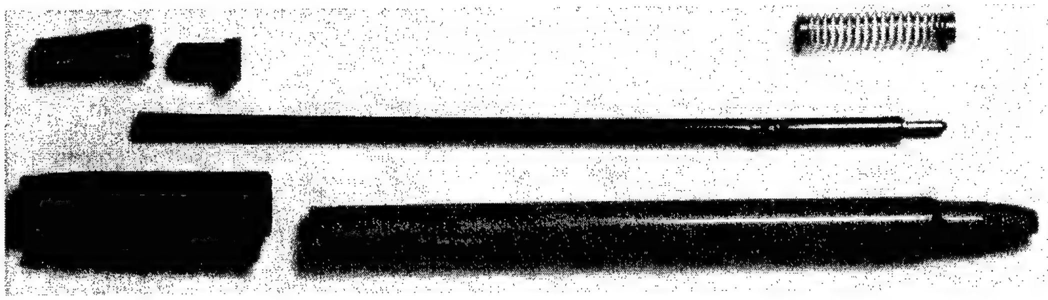


Figure 6.15: Orange Advertising Pen Exploded View

Two user operations are modeled for the staple remover, and four user operations are modeled for the pens. The operations are derived from the activity diagrams for the products, Figure 6.16 for the staple removers, and Figure 6.17 for the pens. The activities for the staple remover include: *Grasp/Release Staple, and Pull Staple*. The *grasp/release staple* operation is really two operations that are reciprocal to one another. The efforts and motions are of the same type for both, but the directions are opposite. The *pull staple* operation is carried out when the staple is actually removed from the paper stack. The activities for the pen include: *Extend/Retract Insert*, *Write*, *Refill*, *Clip/Store*. The *extend/retract* operation allows the ink Insert to be extended and retracted for writing and storage respectively. The *write* operation is used whenever the pen is being used as a writing instrument. The *refill* operation is used when the ink Insert must be replaced. An additional benefit to modeling the *refill* operation is that it is very similar to the assembly operation associated with the manufacturing process. The *clip/store* operation is carried out when the built in Clip Spring is used to secure the pen to a suitable object.

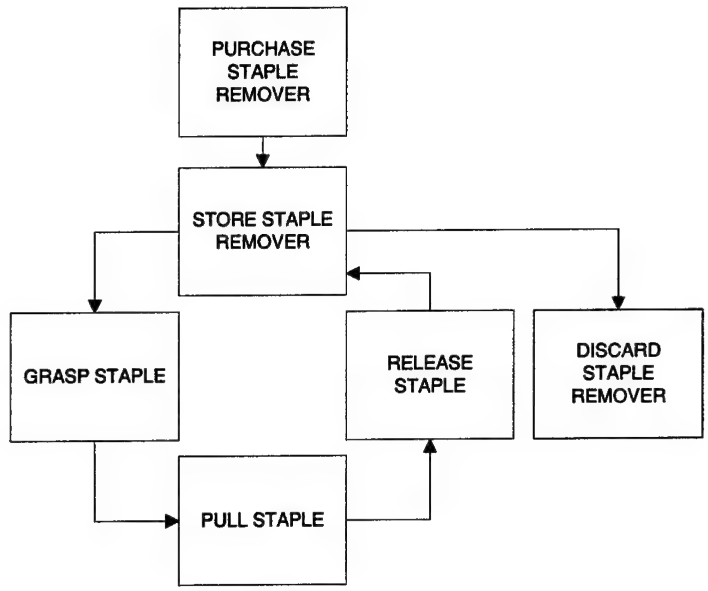


Figure 6.16: Staple Remover Activity Diagram

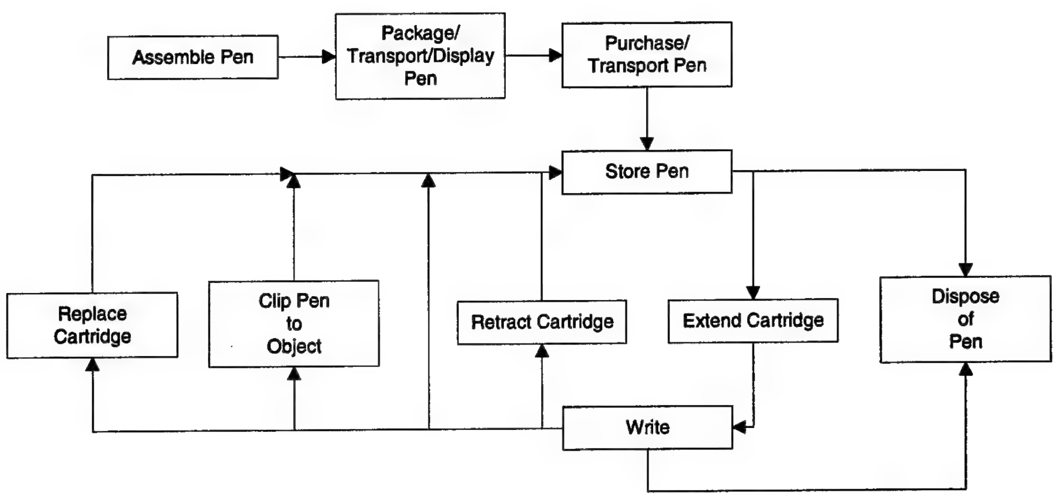


Figure 6.17: Pen activity Diagram

6.4.2 - The Assignment

This section is a brief summary of the assignment given to the students. The subjects were given the both of the products as well as the diagrams shown in Figure 6.11

and Figure 6.14. In addition, they were given Functional Models, Activity Diagrams, Component Names and Numbers, and Adjacency Matrices for each of the products. The assignment is as follows:

> Your task is to develop the effort flow diagrams and use them to create evolutionary designs for the products of the study. With this goal in mind, the following tasks are assigned for the pen and staple remover products:
>
> Apply the effort flow analysis methodology.
>
> Label all effort flow diagrams using only those component names and/or numbers shown in the given figures and tables,
>
> After constructing the initial effort flow diagram for each product, fill in the adjacency matrix for each product (Table 6.14 & Table 6.15).
>
> Develop a redesign concept using the N-Link, C-Link, and R-Link design guidelines.
>
> Model the redesign concept in an effort flow diagram.
>
> Sketch the redesign concept.

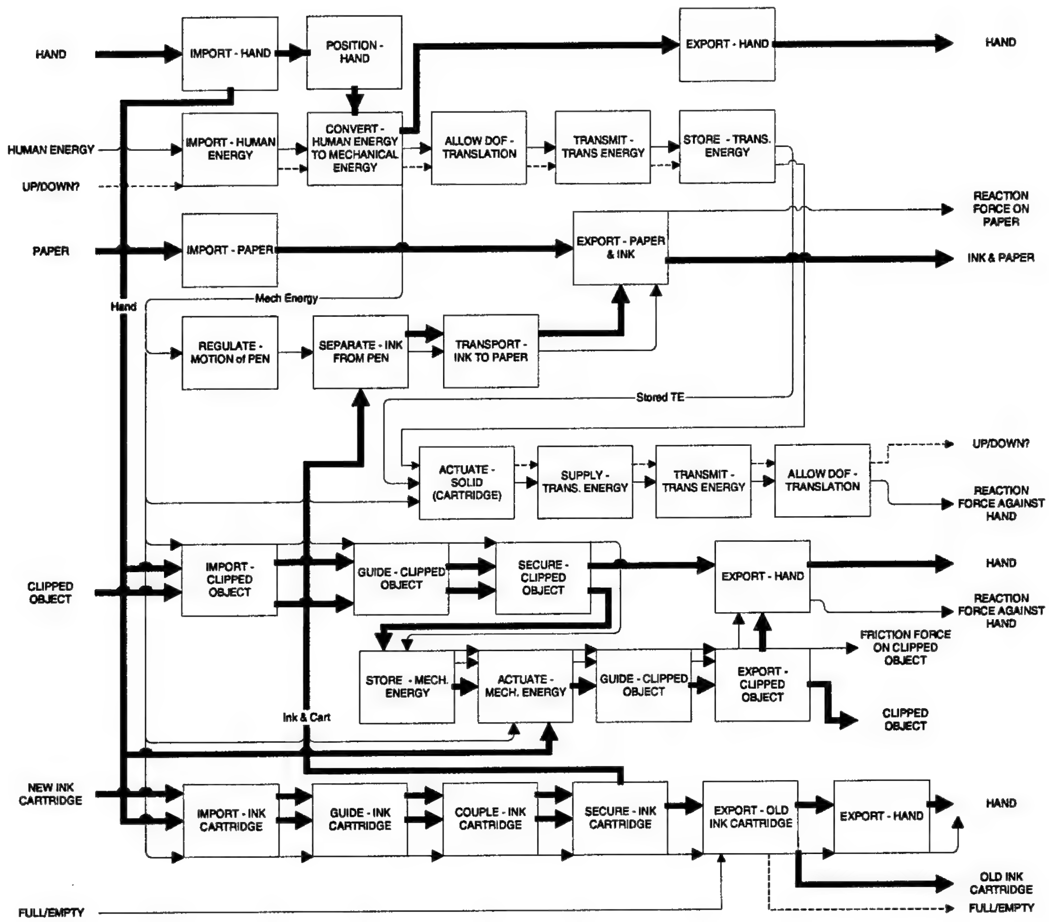


Figure 6.18: Pens Function Structure

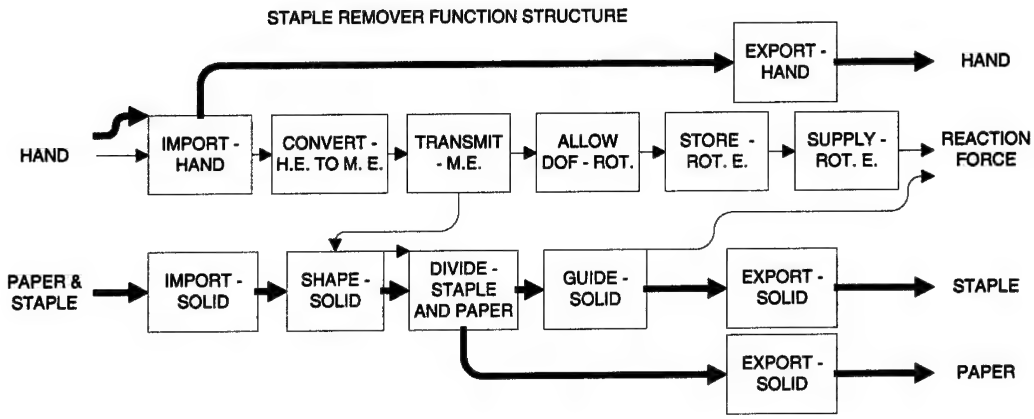


Figure 6.19: Staple Remover Function Structure

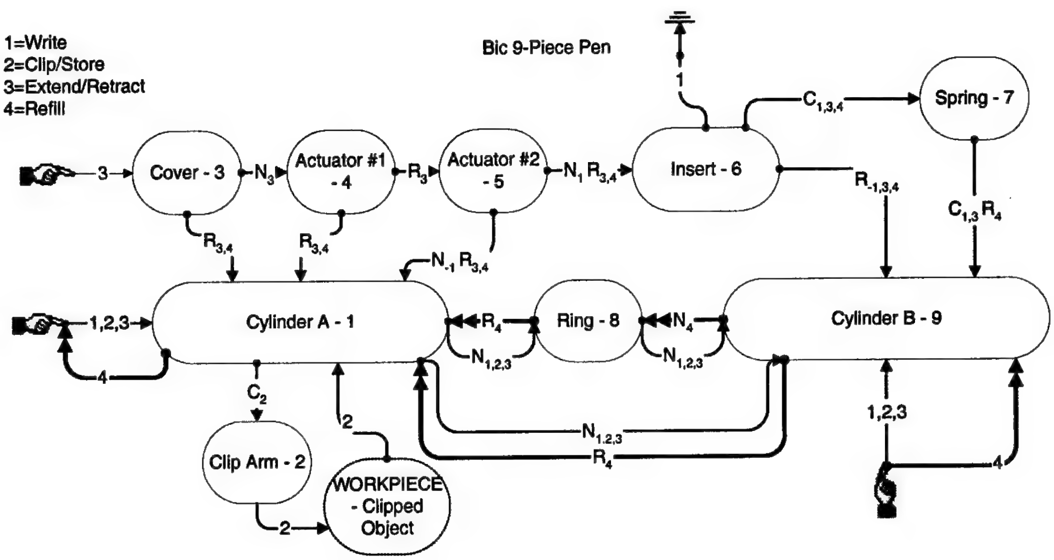


Figure 6.20: Bic® Pen Effort Flow Diagram

Table 6.14: Adjacency Matrix for Bic® Pen

Component Name	Cylinder A	Clip Arm	Cover	Actuator 1	Actuator 2	Insert	Spring	Ring	Cylinder B
Cylinder A	E	1	1	1	1			1	1
Clip Arm	1	E							
Cover	1		E	1					
Actuator 1	1		1	I	1				
Actuator 2	1			1	I	1			
Insert					1	E	1		1
Spring						1	I		1
Ring	1							I	1
Cylinder B	1					1	1	1	E

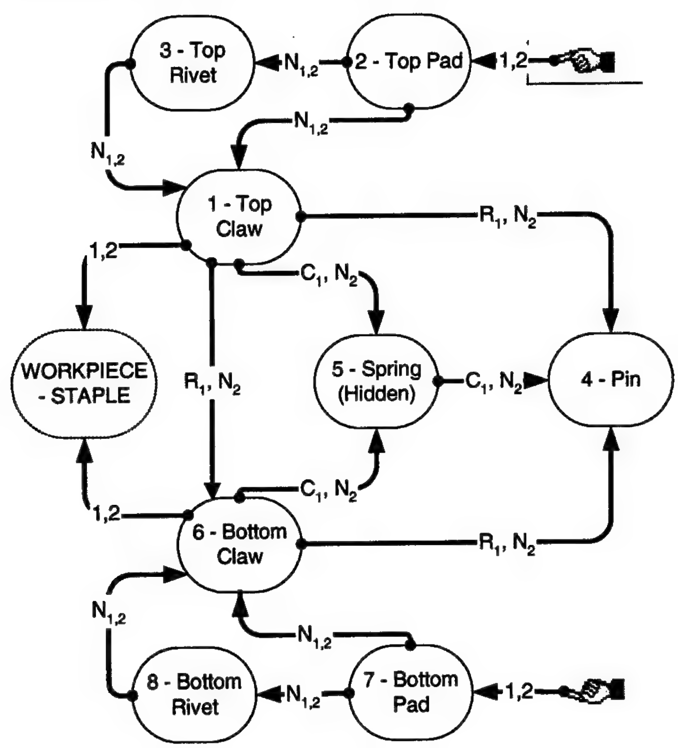


Figure 6.21: Staple Remover Effort Flow Diagram

Table 6.15: Adjacency Matrix for Staple Remover

Component Name	Top Claw	Top Pad	Top Rivet	Pin	Sping	Bottom Claw	Bottom Pad	Bottom Rivet
Top Claw	E	1	1	1	1	1		
Top Pad	1	E	1					
Top Rivet	1	1	I					
Pin	1			I	1	1		
Spring	1			1	I	1		
Bottom Claw	1			1	1	E		1
Bottom Pad					1	1	E	1
Bottom Rivet						1	1	I

6.4.3 - Study Results

The results of the study are based on objective measures with some amount of subjectivity involved in the measurement of link characterization accuracy. The objective measures include the total interfaces correctly identified in the adjacency matrix, the interface characterizations correctly identified, and the number of components in the evolved product.

Subjectivity comes into the evaluation of the link characterization measures, and is related to the subjectivity of design as a process. Design is a socio-technical endeavor carried out by human agents. No two agents approach the process in exactly the same manner; the result is that each agent produces slightly different design results based on their personal biases and experiences. These differences manifest themselves in the modeling decisions made by the subjects. Each subject in this experiment made different, though completely valid, assumptions about how to model the operation of the products. These assumptions lead to differences in characterization of interfaces when compared to the standard model for the study. This is especially true when the interactions are ancillary or incidental to the primary operation of the product.

An example of ancillary or incidental effort transmission occurs between *Cylinder A* and the *Cap* during the *Extend/Retract* operation in the Ball Point pen. The

effort flow in question is denoted by $\mathbf{R}_{34}$ link between the *Cylinder A* and *Cap* components in the diagram for the pen shown in Figure 6.21. The *Cap* does indeed contact *Cylinder A* during the *Extend/Retract* operation, but the dominant effort flow in the operation is between the *Cap* and *Actuator 1*. In the interest of completeness, the standard effort flow diagram was developed with all effort flow paths annotated, but several of the test subjects made assumptions about the primacy of certain effort flows and chose to disregard lesser ones. For this reason, a subjective evaluation of several flows was required to ensure these different characterizations did not significantly skew the results. The data from the study is presented in Table 6.16, Table 6.17, Table 6.18, and Table 6.19.

Table 6.16: Repeatability Study Results for Interface Identification

Product	**Measure**	**Result**
	Number of Subjects in study	17
Staple Remover	Actual Internal Interfaces for product	12
	Reported Internal Interfaces	11.1 Std dev 1.75
Pen	Actual Internal Interfaces	13
	Reported Internal Interfaces	12 Std dev 0.61

The first set of data in Table 6.16 shows the accuracy with which the subjects were able to identify the unique internal interfaces within each product. A unique internal interface is an individual link in the effort flow diagram, independent of the number of operations and characterizations for that link. Both products had similar numbers of internal interfaces, and the subjects were able to identify those interfaces with reasonable accuracy. In fact, the accuracy exhibited for the pen, an arguably more complex product, produced the most accurate results. It is thought that this improved accuracy is related to the learning curve associated with the process. By analyzing the staple remover prior to analyzing the pen, the subjects moved further along in the learning process and thus produced better results with the second product.

Most of the entries in Table 6.17 are self-explanatory, but some require further explanation. The entries for Characterization Error by Link Type capture the number of each link type in both the products in the Link Type column. The Result column contains

the number of characterization errors observed over all the subjects divided by the number of subjects to provide the average number of characterization errors per subject. This result is then divided by the number of links of that type to indicate the average percentage, in parenthesis, of the link characterizations that were in error for that link type. Under the heading of Characterization error by Operation, the Link Distribution entries indicate the distribution of the link types that are active for the operation under consideration. With the presentation of the results explained, it is possible to understand their implications.

Table 6.17: Repeatability Study Results for Interface Characterization in the Staple Remover Product

Product	**Measure**	**Link Type (Freq)**	**Result**
	Number of Subjects in study		17
Staple Remover	Possible Interface Characterizations		24
	Average Interface Characterizations		19.35 std dev = 2.52
	Average Correct Interface Characterization		12.7 std dev = 5.26
	Characterization error by Link Type	N (18) C (3) R (3)	105/17 = 6.18 (34%) 10/17 = 0.59 (20%) 13/17 = 0.76 (25%)
	Characterization error by Operation:		
	Clamp/ Release		2.38
	Link Distribution		N=6 (50%) C=3 (25%) R=3 (25%)
	Pull Staple		5.09
	Link Distribution		N=12 (100%) C=0 R=0

Table 6.18: Repeatability Study Results for Interface Characterization in the Pen Product

Product	Measure	Link Type (Freq)	Result
Pen	Possible Interface Characterizations		34
	Average Interface Characterizations		23.35 std dev = 9.49
	Average Correct Interface Characterizations		15.9 std dev = 5.23
	Mischaracterization by Link Type	N (13) C (6) R (15)	85/17 = 5.00 (38%) 32/17 = 1.88 (31%) 126/17 = 7.41 (49%)
	Mischaracterization by Operation:		
	Write		4.26
	Link Distribution		N=5 (62.5%) C=2 (25%) R=1 (12.5%)
	Clip/ Store		3.35
	Link Distribution		N=3 (75%) C=1 (25%) R=0
	Extend/ Retract		3.09
	Link Distribution		N=4 (33%) C=2 (17%) R=6 (50%)
	Refill		7.35
	Link Distribution		N=1 (10%) C=1 (10%) R=8 (80%)

The data contained in Table 6.17 and Table 6.18 captures the accuracy with which the subjects were able to characterize the interactions between components using the effort flow analysis link type definitions. The approach taken here is to first count the gross number of possible characterizations for the standard effort flow diagram of each product, 24 and 34 for the staple remover and the pen respectively, and compare that number to the average number of characterizations found by the subjects. This was done without regard to the link type chosen. The data shows that although the participants were able to identify the interfaces in the product, they tended to under identify the various types of relative motion interface interactions. Under identification and characterization is especially evident in the pen, where the link characterizations are on average 33% below the standard. The standard deviation for this data is rather large,

partly due to one subject who over characterized the pen interfaces by 50%, or nearly twice the average with a characterization total of 53. Part of the under characterization demonstrated by the subjects is attributed to the standard effort flow diagram. As mentioned previously, all interactions are captured in the standard, which is not necessarily the level of modeling fidelity chosen by each subject.

In addition to the gross number of interface characterizations, the data was evaluated for correct characterization of the individual interfaces for each operation and for each link type. To accomplish this task, each incorrectly characterized interface was counted with a weight of one with provisions made for interfaces where an absolute correct characterization could not be established. An example of a characterization with more than one correct result occurs between the *Cylinders* and the *Ring* of the pen. The two possible configurations for this set of interfaces are shown in Figure 6.22. The interface between *Cylinder A* and the *Ring* could be characterized as either an $\mathbf{N_4}$ or an $\mathbf{R_4}$ with the corresponding opposite characterizations between the *Ring* and *Cylinder B*.

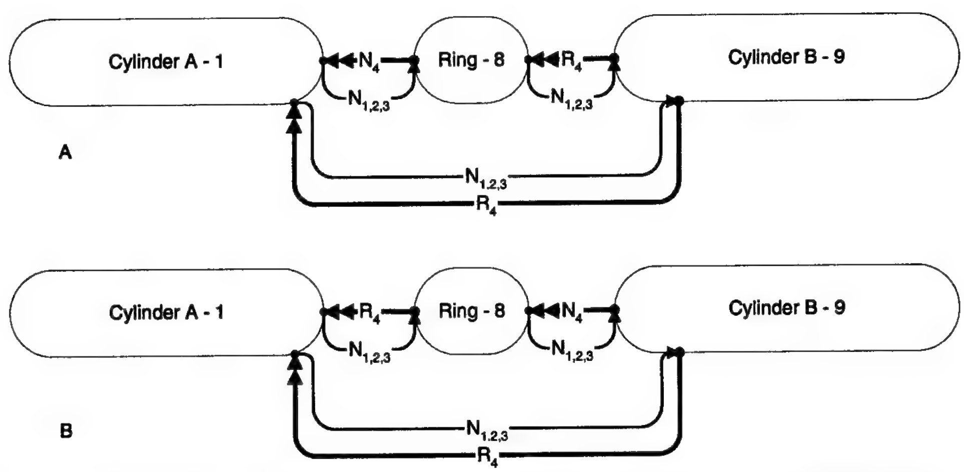


Figure 6.22: Two Possible Interface Characterizations for Pen

Because of the possibility of variation in the results due to permutations in the correct model, and due to modeling decisions made by the subjects, analysis of the interface characterization data required that subjective adjustments be made to the scoring system used for this portion of the data. In cases where two correct models could

have been reached, both were accepted. The adjustments were made primarily to flows where modeling assumptions resulted in apparent errors in the characterization of a link. The method of adjustment was to weight the mischaracterized link as half wrong, (or half right for the optimist), rather than the standard weight of 1.0.

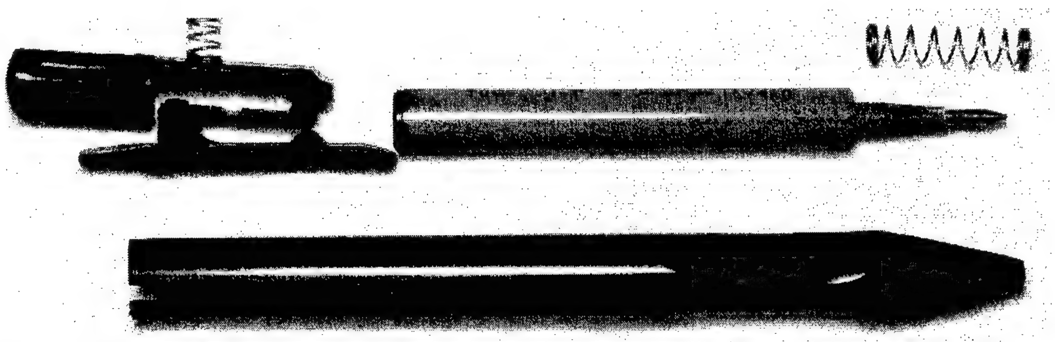
In both products, C-Links are consistently the most accurately characterized, followed by N-Links and finally R-Links, better performance with the C-Links may be due to the fact that they are the least frequently observed link type, thus drawing more scrutiny from the participants due to their novelty. According to the ranges present in the data, a C-Link has a 69-80% chance of being correctly identified and characterized. The N-Link is next best with a 66-68% chance of being identified and characterized correctly. Finally, the R-Link has the least chance of being correctly identified and characterized at 51-75%.

The primary reason for the difficulty with R-Links in this study comes from the *Refill* operation associated with the pen, where 80% of the active links are R-Links. In the pen, the R-Links contribute a disproportionately high percentage of the errors; they contribute 40% of the total error for the entire model but only represent 31% of the links. The *Refill* operation is arguably the most subjective of the operations to characterize, owed primarily to the treatment of the components that are free to move during the removal of the ink *Insert*. This difficulty, while notable, does not seem to have a significant effect of the outcome of product evolution.

Table 6.19: Repeatability Study Results for Product Evolution

Product	Measure	Result
	Number of Subjects in study	17
Staple Remover	Initial Number of Components	8
	Average number of components in evolved product	1.53 std dev = 1.07
	Expected number of components in evolved product	2
Pen	Initial Number of Components	9
	Average number of components in evolved product	4.17 std dev = 1.29
	Expected number of components in evolved product	5

Finally, the data contained in Table 6.19 represents the results of the subjects design efforts with each of the products. The results indicate that each subject was able to push product evolution to near that observed in the existing examples of evolved products for the product group in question. The Staple remover product group has a demonstrated evolution to two components demonstrated by the Bostich® staple remover shown in Figure 6.13. The average number of components in the evolved staple remover of the subjects is slightly below this number at 1.53 components. This difference is thought to be because the subjects were not constrained by the issues of manufacturability or cost, and hence were able to present evolved concepts that went beyond what industry is currently capable of, or willing to pursue. The pen product group has a demonstrated evolution of five components demonstrated by the Pilot Explorer® pen shown in Figure 6.23, while the average number of evolved pen components found by the subjects is 4.17 components. The difference is attributed to the



subjects' freedom to create concept variants without constraints.

Figure 6.23: Pilot Explorer® Schematic

All the subjects, save for one, were able to identify opportunities associated with the fundamental guidelines for N-Links and C-Links. The N-Link guideline was applied to the staple remover to eliminate the *Rivets* and the *Pads*, and was applied to the pen to combine the *Cover* with *Actuator 1* and to eliminate the *Ring*. The C-Link guideline was applied to the staple remover to incorporate the *Spring* into one of the *Claw* components, and was used to incorporate the *Clip* into *Cylinder A* in the pen.

Ultimately, the results of the product evolution phase indicate that the modeling decisions made by the subjects were sound. The method, in these two cases, is insensitive to the apparent errors in the link characterizations. This is a positive result from the standpoint that even though link characterization varies between practitioners, the results still tend toward the desired goal of component combination and complexity reduction.

The goal of this study is to show that effort flow analysis is repeatable when applied to the systematic evolution of products in the domain of mechanical effort transmitters. The results for the chosen products indicate the method is successful in directing the designer to both rigid body and compliant evolutionary solutions. The study subjects were able to identify and act on opportunities leading to evolved solutions known by the examiner to exist in the market place. There are issues with the repeatability of interface characterization, but interface identification and product evolution are both shown to be accurate and repeatable.

6.5 - CHAPTER CONCLUSIONS

Effort flow analysis as a research topic has reached a level of maturity where it may be exported to industry for use in the directed evolution of artifacts in the domain of mechanical effort transmitters. This level of maturity is the ultimate goal of this research effort. Reaching the industrial implementation stage initiates a feedback channel that allows the method to continue evolving toward a broader spectrum of applicability [50]. Evidence that effort flow analysis has reached this level is provided by the successes noted in the Sun Visor example from the *Industrial Example Using the Force Flow Method* section of Chapter 1, and the product evolution results from the repeatability study of this chapter. The next step in moving the method to broader applicability is to apply it to a product that has not been significantly evolved, and then observe the results.

Chapter 7 - Product Evolution Example

7.1 - INTRODUCTION

When it comes to the validation of a proposal or theory in design science, "the proof is in the product." This is utilitarian view of design science fits well with the practitioner's focus taken in the previous chapter. In this chapter, the proof of the effort flow analysis method is demonstrated by its application to a product that is familiar, yet has not evolved considerably in the recent past. After applying the effort flow analysis in its entirety the results are evaluated against the evolutionary goals and are compared to several design variants that resulted using some other more ad hoc design methods.

7.2 - THE PRODUCT

The search for a suitable subject was based on the presence several key characteristics. The characteristics desired are that the product must be: mechanical in nature, provide relative motion functionality, and have some form of human interface. The search turned up a product that is common to nearly all parts of the world; it is mechanical in nature; operation of the product requires the provision of relative motion functions and it uses a significant number of components to provide those functions, and it is operated by human power.

Figure 7.1: The Product

The product selected for the redesign effort is a golf umbrella. Construction of the umbrella requires the manufacture and assembly of over 120 separate components, the majority of which are used in constructing the eight deformable beams that support the canopy. Effort flow analysis used to evolve this product, the result of which is a functional prototype.

7.3 - The Prototyping Plan

The prototyping plan for the Umbrella Re-design Project is developed using the prototype partitioning methodology proposed by Moe [162]. The result is a prototype partitioning strategy tailored to the specifics of this project. The strategy prescribed for the umbrella redesign project is summarized in the following 5 points quoted from [163]:

> The umbrella re-design effort should be broken into two iterations. Each iteration should start with concepts of what will be prototyped. Each iteration should end with a design review in which the prototypes are evaluated against the project requirements.

In each iteration, the design, fabrication, and testing of at least three different concepts should be attempted, concurrently.

Midway through each iteration the initial designs concepts and project timeline should be reevaluated and adjusted based upon any new and relevant information.

The design review at the end of the first iteration should evaluate the demonstration requirements (e.g. are the recommendations of the design evaluation process implemented, does the new componentry fit in place, can it be assembled, is there a locked closed position, is there a locked open position, is the device self-actuating in opening, etc.) Also, lessons learned related to design should be reported.

The design review at the end of the second iteration should evaluate both demonstration requirements and functional requirements (e.g. what is the ultimate strength of the device, what is its closed volume, what is its weight, what is the manufacturing cost, etc.). Total project expenses should be reported. Also, a clear statement of design success or failure should be made.
Full Text included in Appendix D.

Three concepts were initially prototyped based on this plan, two of which made it to the final stages of development. The prototyping plan was followed as closely as possible, with various revisions on dates and objectives, through the entire prototyping effort. The goal of the prototyping effort is to demonstrate the effectiveness of effort flow analysis in evolving an existing product. The prototype provides a physical embodiment of a design concept generated by effort flow analysis. Application of effort flow analysis to the product begins with definition of the project goal.

7.4 - Application of the Effort Flow Analysis Methodology

The practitioner's version of the effort flow analysis methodology is used to direct the evolution of the umbrella product. The initial phases of the process are shown in Figure 7.2, and the results of their application follow.

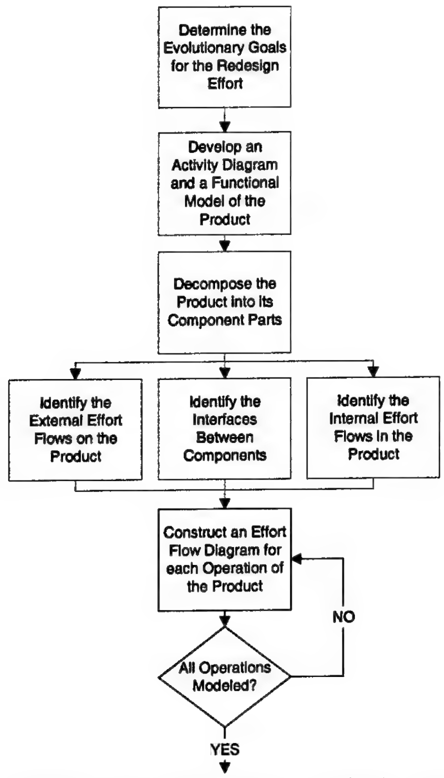


Figure 7.2: Initial Steps in the Effort Flow Analysis Process Model

7.4.1 - Evolutionary Goal

The goal of this redesign effort is first of all to demonstrate the effort flow analysis methodology. The byproduct of this demonstration is the revolution of the product. The product has essentially reached a commodity state in the S-Curve model of product evolution [1]. In the commodity phase of evolution, product manufacturers maintain profit margins by achieving superior economies of scale in manufacturing and assembly or by jumping to another curve with a revolutionary product. To be successful, the application of effort flow analysis to a commodity product needs to produce a disruptive technology [102] or make an incremental improvement in the manufacturability and assemblability of the existing product that is significant enough to overcome the costs associated with the change.

If a disruptive technology is sought, effort flow analysis must pursue the revolutionary path, which has implications for the prosecution of effort flow analysis.

One implication is that design variants that include only incremental evolutionary steps will not be pursued; rather the process will be pushed to the furthest extent possible before a design concept is developed. As concepts are found to be infeasible, then lower level variants will be pursued, or the design effort will be terminated if sufficient evolutionary progress cannot be achieved.

7.4.2 - Activity Diagram and Functional Model

The activity diagram is developed by observing the product in use by others, as well as by personally experiencing the product. Note that although the activities associated with manufacturing and assembly are included in the activity diagram of Figure 7.3; they are not treated in detail, as they are not the focus for this redesign effort.

Although assembly activities are not the focus of this example, it is assumed the results of this redesign effort will have a positive impact on both the manufacturability and assemblability of the resulting design. The primary source of improvement is expected to be a reduction in the number of components brought together to produce the umbrella.

"Experiencing" the umbrella through long-term use and observation results in the modeling of four operations in effort flow analysis. These operations are *Open Umbrella for Use*, *Close Umbrella after Use*, *Secure Umbrella Arms Using Strap and Snap*, and *Store Umbrella in Upright Position.*

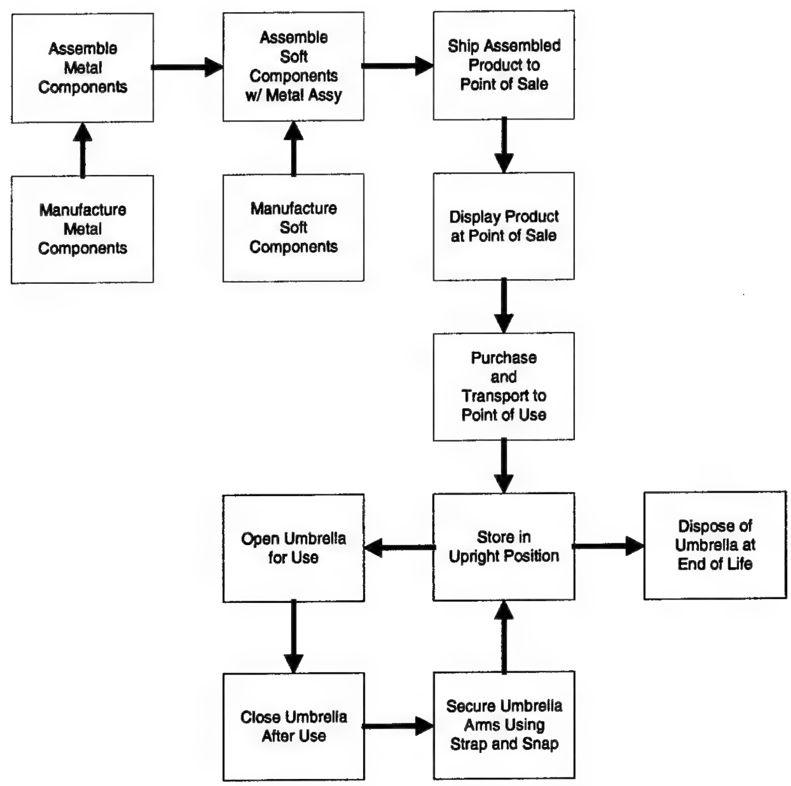


Figure 7.3: Activity Diagram for Umbrella Product

Development of the functional model of an umbrella proceeds from the user operations listed above, as well as the general Customer Needs (CN) associated with an umbrella, and shown in Table 7.1. The CN are based on personal experience only, and do not reflect the results of a formal CN gathering process. The user operations in conjunction with the CN lead directly to the functional model for the umbrella product.

Table 7.1: Customer Needs for an Umbrella

Customer Need
Be Light Weight
Keep the user dry.
Store compactly
Open easily
Lock in the open position

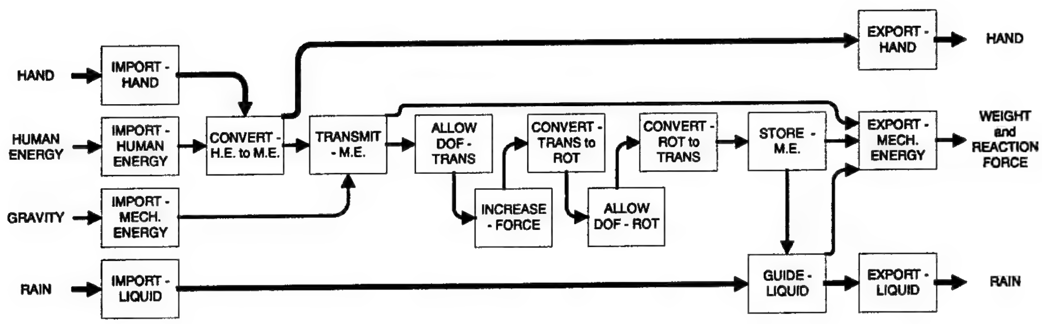


Figure 7.4: Function Structure for Umbrella Product

The functional model shown in Figure 7.4 represents the functions provided by the umbrella product. The functional model represents the input output relationship for the fundamental flows from the design of technical systems, namely Energy, Material, and Information [49]. The function structure is form independent; the only indication of the domain of the product comes from the relative motion functions provided for translation and rotation, and the presence of mechanical energy flows. These relative motion functions are exactly the type desired in an example product, and are the strongest motivation for choosing this product. With the user operations identified, and the customer needs, and functional model established, product decomposition begins.

7.4.3 - Product Decomposition

Product decomposition proceeds with component naming. In all, there are more than 140 components involved in the construction of the umbrella under consideration. This part count does not include the various pieces of thread needed to sew the canopy

together, as they do not demonstrate the desired functionality, and do not appear to provide significant insights into the overall mechanical system.

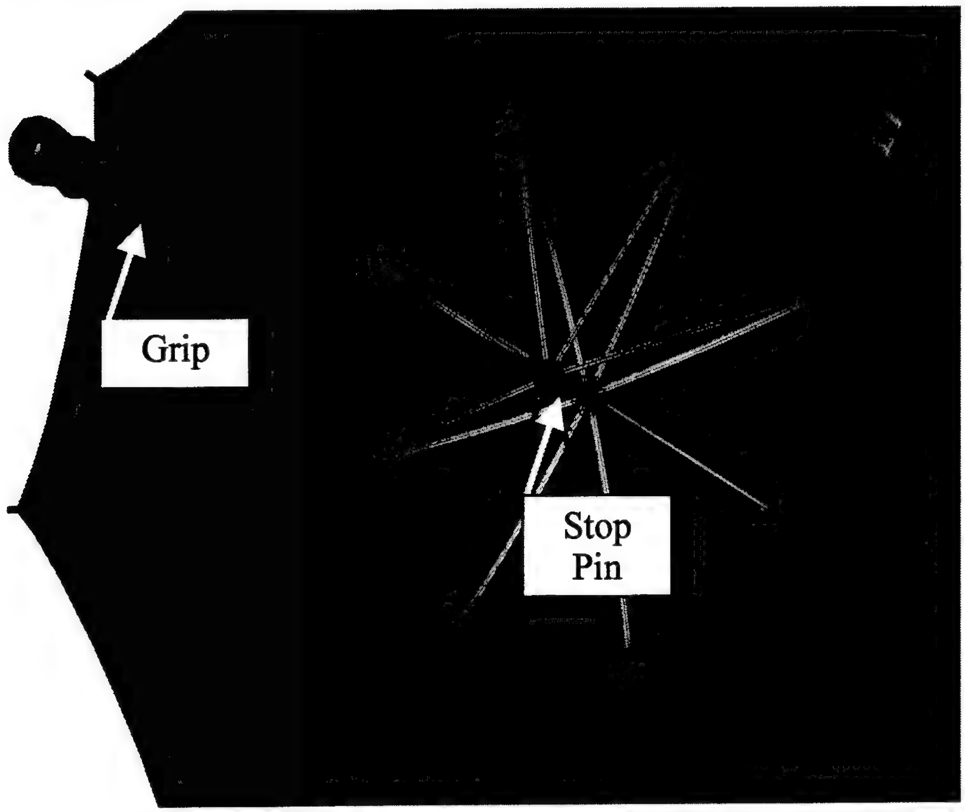


Figure 7.5: Umbrella Structure

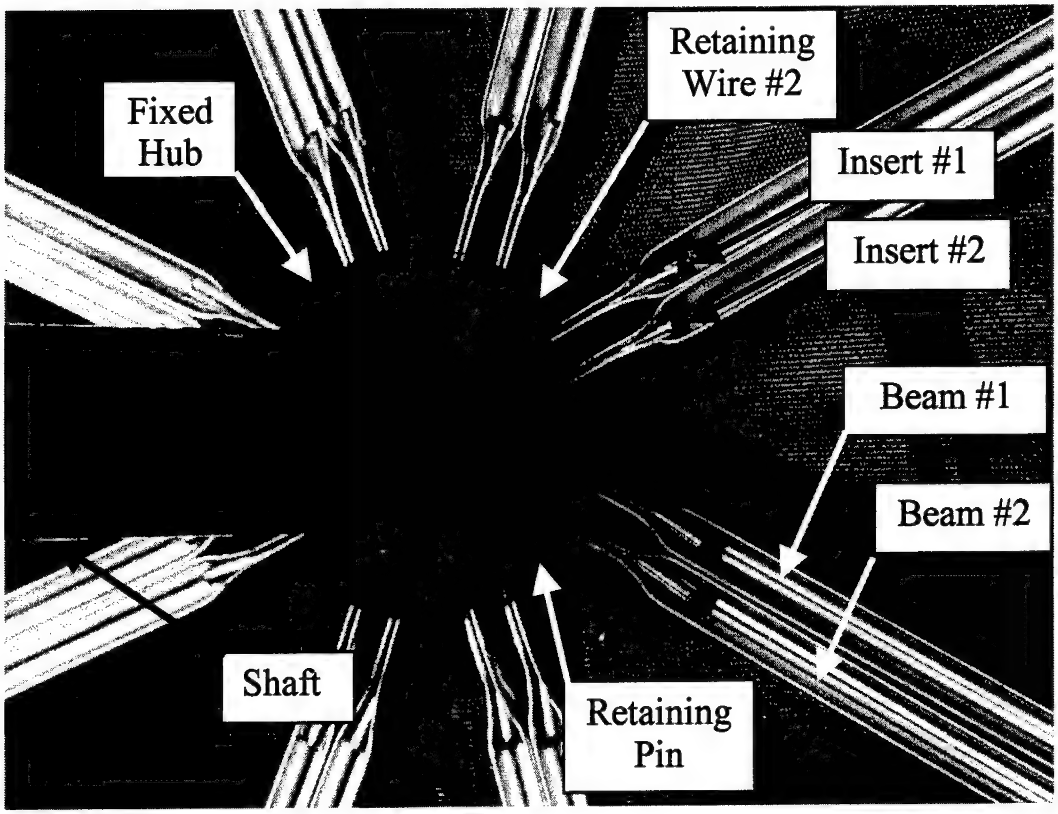


Figure 7.6: Umbrella Fixed Hub Structure

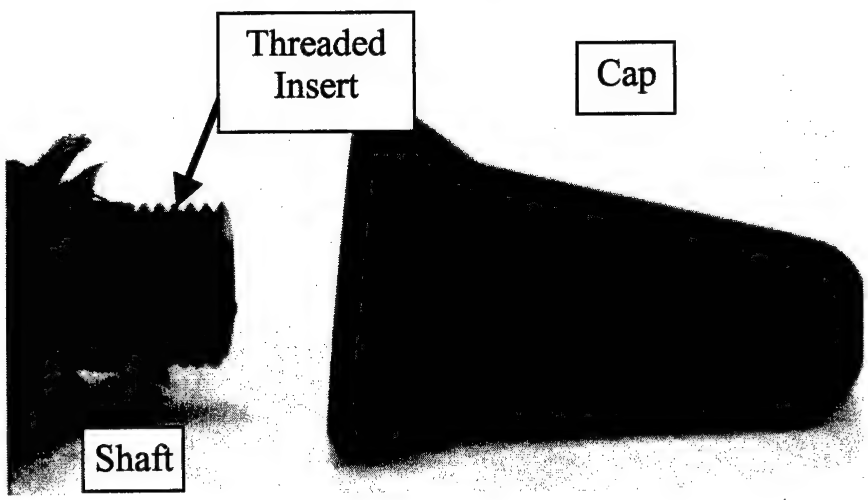


Figure 7.7: Umbrella Shaft, Threaded Insert, and Cap

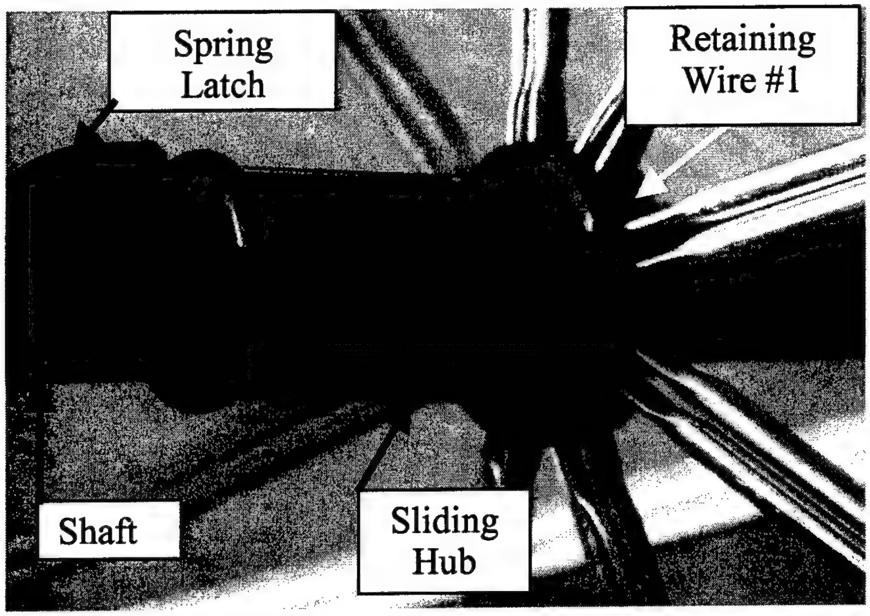


Figure 7.8: Umbrella Sliding Hub, Retaining Wire, Spring Latch and Shaft

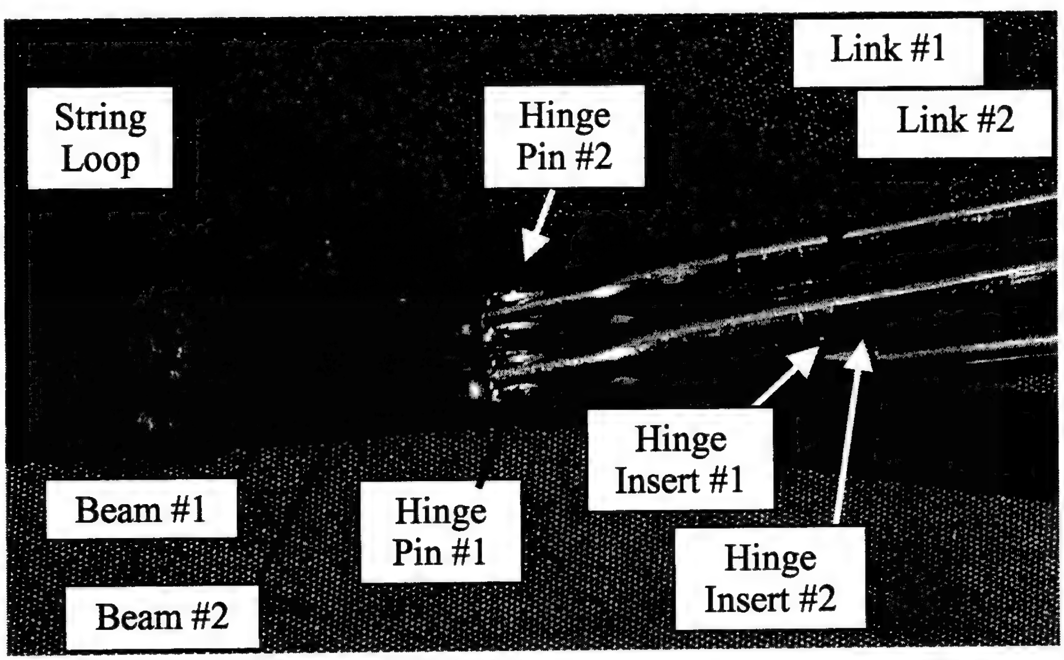


Figure 7.9: Umbrella Beams, Hinge Pins, Hinge Inserts, Links, and String Loops

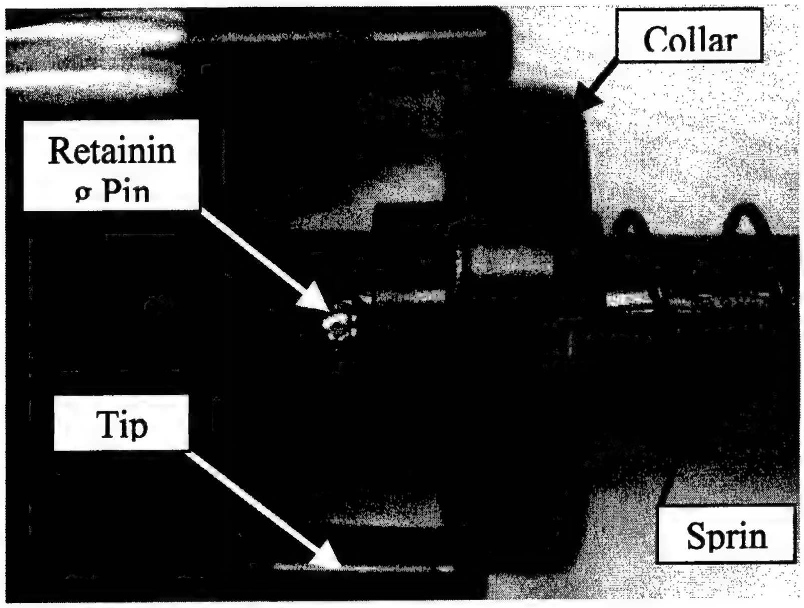


Figure 7.10: Umbrella Tim, Retaining Pin, Collar and Spring

Table 7.2: Component Numbers and Names

Component Number	Component Name	Component Number	Component Name
1	Grip	17	Tip (8 ea)
2	Shaft	18	Cap
3	Fixed Hub	19	Collar
4	Sliding Hub	20	Spring
5	Retaining Wire #1	21	Spring Latch
6	Retaining Wire #2	22	Retaining Pin
7	Insert #1 (8 ea)	23	Canopy Membrane
8	Insert #2 (8 ea)	24	Thread Loop #1 (8 ea)
9	Beam #1 (8 ea)	25	Thread Loop #2 (8 ea)
10	Beam #2 (8 ea)	26	Threaded Insert
11	Hinge Insert #1 (8 ea)	27	Hub Retaining Pin
12	Hinge Insert #2 (8 ea)	28	Closure Strap
13	Hinge Pin #1 (8 ea)	29	Male Coupler
14	Hinge Pin #2 (8 ea)	30	Female Coupler
15	Link #1 (8 ea)	31	Stop Pin
16	Link #2 (8 ea)	32	Insert Sliding #1 (8ea)
		33	Insert Sliding #2 (8ea)

The names for the components of the umbrella are contained in Table 7.2. Note that some of the component names have (8 ea) appended, indicating that there are eight of these components in the product. The external efforts for the product are captured, and contained in Table 7.3. The table shows the type of external effort and its location on the umbrella. The external effort locations are also contained in the diagonal entries of the adjacency matrix in Table 7.4, where an "E" indicates an external interface, and an "I" denotes an internal interface.

Table 7.3: External Efforts and their Locations

External Effort Type	**Location**
Human	Spring Latch
Human	Handle
Human	Sliding Hub
Human	Collar
Human	Closure Strap
Human	Female Coupler
Ground	Cap
Weight	Entire Body, assumed on Shaft

The adjacency matrix also contains all the information on component connectivity for the product model. Note that the matrix is lower triangular, this is possible because component connectivity is symmetric.

Table 7.4: Adjacency Matrix for Umbrella Product (1/8th model for arm assemblies)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	E																																
2	1	I																															
3		1	I																														
4		1		E																													
5			1		I																												
6				1		I																											
7			1		1		I																										
8			1		1			I																									
9							1		I																								
10								1		I																							
11									1		I																						
12										1		I																					
13											1		I																				
14												1		I																			
15				1									1		I																		
16				1										1		I																	
17									1	1							I																
18																		E															
19		1															1		E														
20	1																		1	I													
21		1		1																	E												
22		1																	1			I											
23			1						1	1							1						E										
24									1	1														I									
25									1	1													1		I								
26		1																1					1			I							
27		1	1																								I						
28																							1					E					
29																												1	I				
30																												1	1	E			
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32						1									1																	I	
33						1										1																	I

7.4.4 - Interface and Flow Identification and Characterization

Each of the four operations modeled for the product will generate effort flows in some components and not in others. The easiest way to capture the relative motion characterizations for the interfaces is in the effort flow diagram. For this reason, product decomposition will jump directly to effort flow diagram construction.

7.4.5 - Effort Flow Diagram Construction

The evolutionary goal for the redesign of the umbrella is to create a revolutionary product (disruptive technology), indicating that the product should be completely decomposed using the functional component representation for all multi-functional components in the product. The umbrella product is rather primitive with regard to function sharing; hence, the functional component representation will be dispensed with for this example.

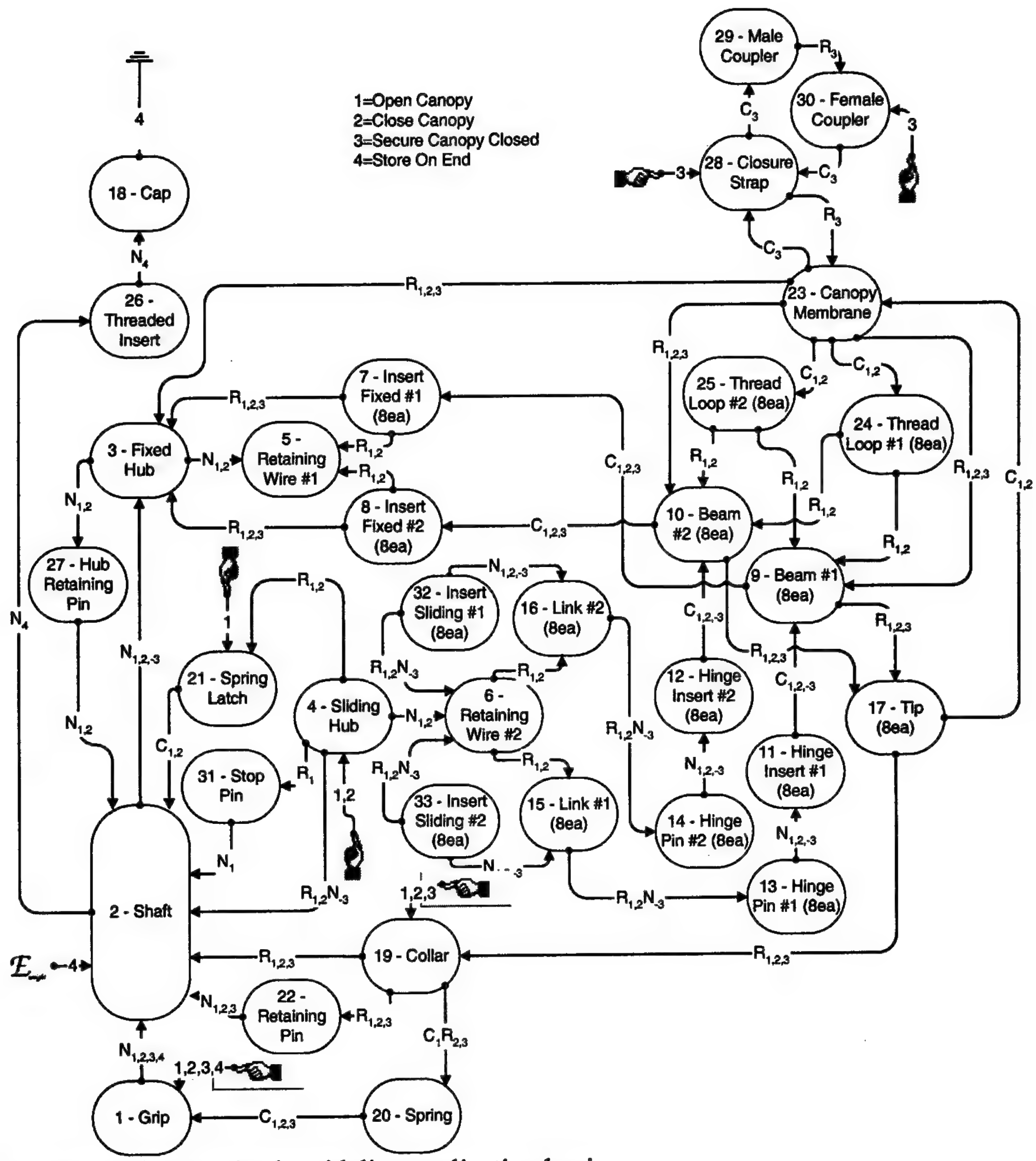
The effort flow diagrams are generated based on the adjacency matrix. The nodes of the diagram are laid out to mimic the layout of the product, and the connectivity is represented using links between the nodes. The overall effort flow diagram for the umbrella is shown in Figure 7.11. Symmetry in the product is used to reduce the diagram complexity by modeling only one of the eight arm assemblies. Product evolution concepts generated for one arm are equally applicable to all the arms.

The effort flow diagram shown in Figure 7.11 is an aggregation of the four diagrams that result from modeling the four operations identified from the activity diagram. The following are the modeling assumptions made in constructing the diagram:

1. The distributed interface between the closure strap and the canopy can be represented as a single R-link
2. The weight of the entire umbrella is concentrated as an external effort on the shaft and is represented by the script E.
3. The only loads associated with storage are those that act through the shaft to the ground.
4. The Canopy Membrane (23) does not impart significant force on the Threaded Insert (26) and the Cap (18) during the open and close operations.
5. Components such as thread used to sew the canopy membrane together do not need to be modeled, i.e. the membrane is a subassembly that will not be analyzed.
6. One arm assembly can be modeled and the results extended to the other arm assemblies in the product.

7. The interaction between the twin components of each arm assembly is negligible, and any incidental interfaces between the two can be neglected.

These assumptions allow the diagram to be simplified without loss of fidelity in the product model. With the assumptions known, the diagram constructed, and the



interfaces characterized, guideline application begins.

Figure 7.11: Effort Flow Diagram for 1/8th Model of Umbrella

7.4.6 - Guideline Application

The order of application for the effort flow analysis guidelines is given in Figure 7.12, where Figure 7.12 represents a portion of the overall effort flow analysis methodology.

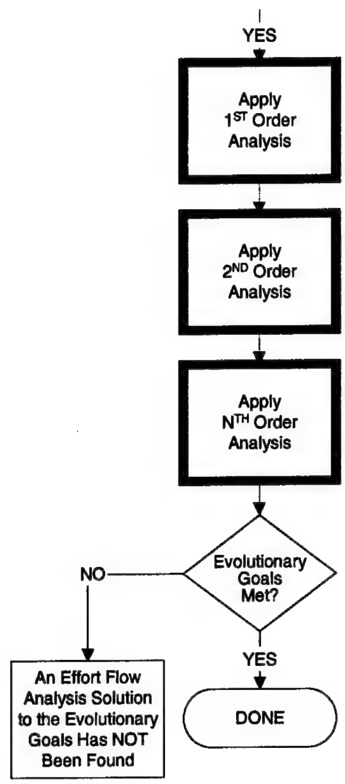


Figure 7.12: Guideline Application Section of Overall Effort Flow Analysis Flow Chart

7.4.6.1 - 1st Order Analysis

Figure 7.13 highlights the process steps for 1st order analysis. The analysis begins by identifying components connected by N-Links to create what are known as N-Groups. These N-Groups are highlighted in the effort flow diagram of Figure 7.14, where components connected only by N-Links are shaded. Figure 7.13 indicates that N-Groups are contracted one at a time, but the number of combinations is small, so all the opportunities will be executed before necessary conditions are checked. The N-Group guideline is applied to the Shaft Group, the Hinge Group & the Hub Group. The result of

combining these components is shown in Figure 7.15. There are now 20 nodes in the diagram, representing 97 parts in the actual product. Because of the revolutionary goal for this project, the example solutions table is not accessed. Were an evolutionary goal sought, the process would continue to concept generation based on the contracted diagram and then a check of the necessary conditions. In seeking a revolutionary product, the necessary conditions are checked as a sanity check.

The necessary conditions for component combination are invoked with a check to determine if the CN can be satisfied with the proposed changes for the product. Each of the proposed combinations is conceivable using parametric changes to the affected components. For example, the Shaft, Handle, and Fixed Hub might be constructed from wood. Since a revolutionary product has not yet been achieved, in depth analysis of the necessary conditions is not conducted, and the 2nd-order analysis phase is initiated.

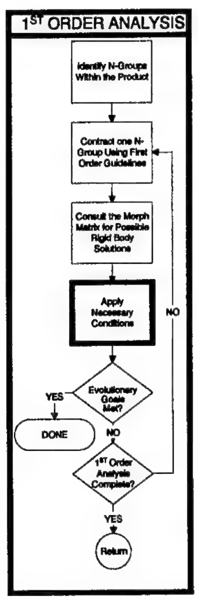


Figure 7.13: 1st-Order Analysis Process Chart

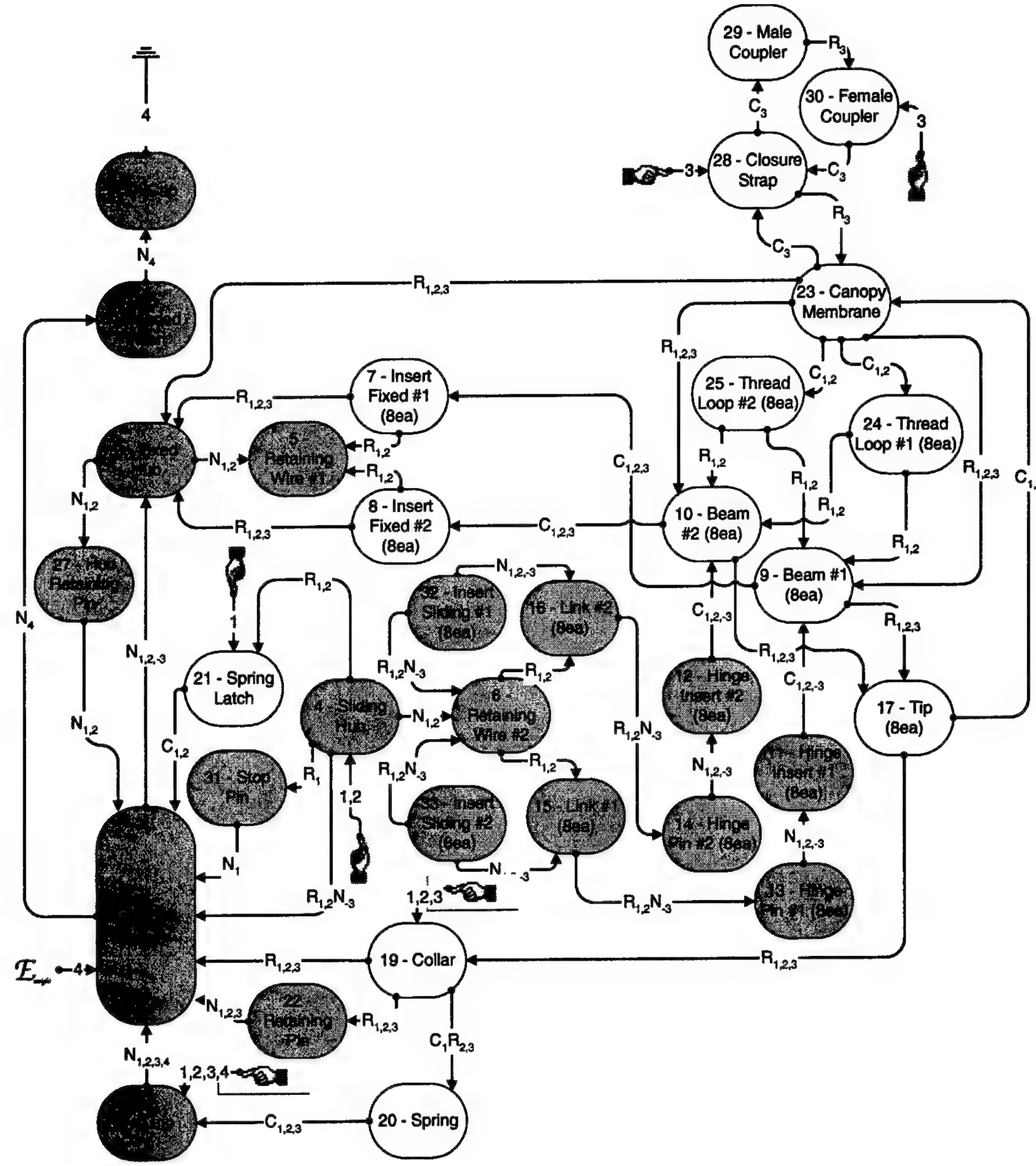


Figure 7.14: N-Group Effort Flow Diagram for Umbrella

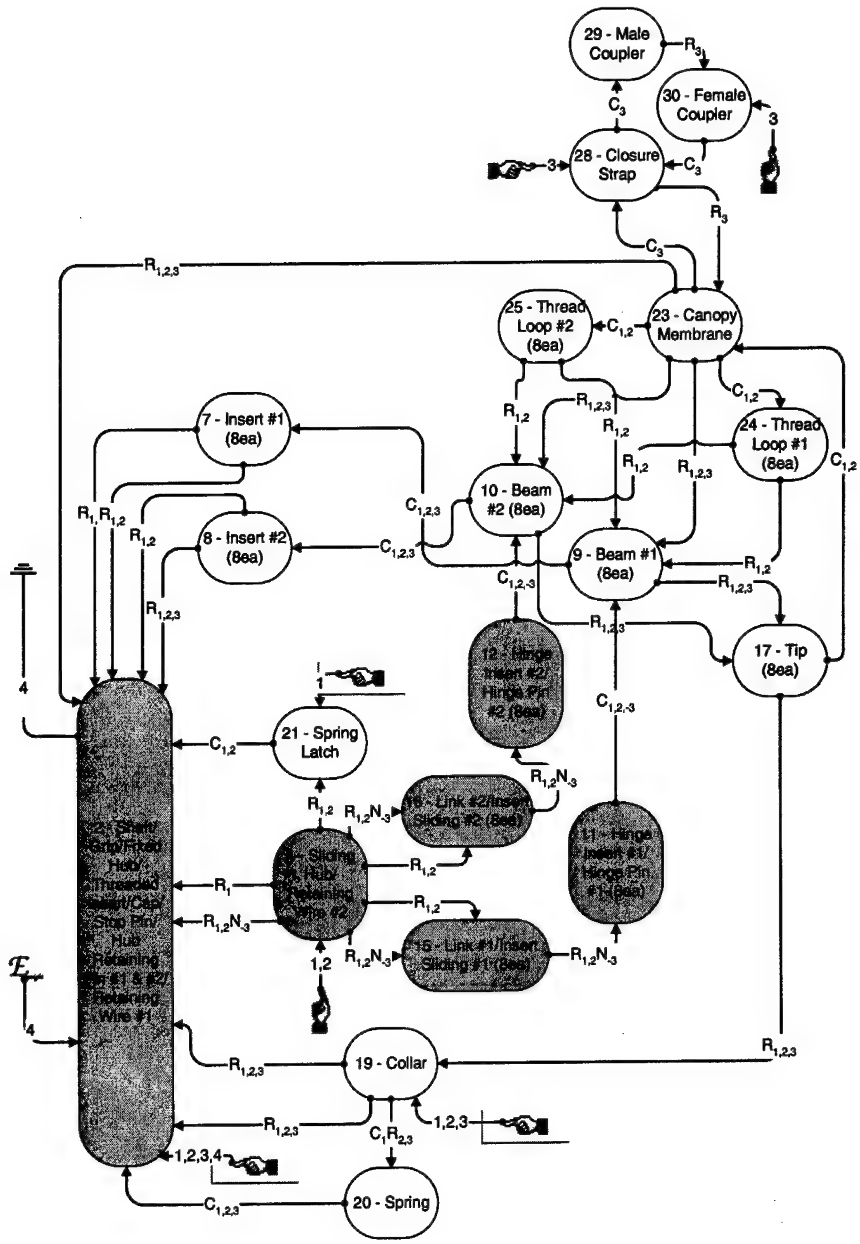


Figure 7.15: Post N-Group Contraction Effort Flow Diagram for Umbrella

7.4.6.2 - 2nd Order Analysis

The 2nd-order analysis phase deals primarily with component combinations across C-Links and CN-Links. The first step (Figure 7.16) is to identify the groups of components connected by C-Links and CN-Links.

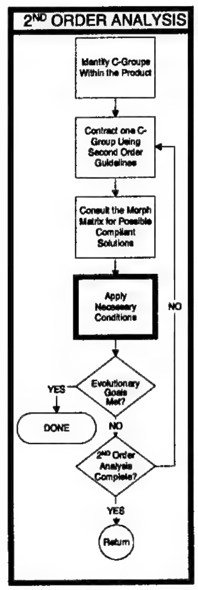


Figure 7.16: 2nd-Order Analysis Process Chart

The initial model for 2nd-order analysis is the result from the 1st-order analysis, and begins with the diagram shown in Figure 7.17. In Figure 7.17, all components connected by C-Links or CN-Links have been highlighted. Nearly all the components in the product are highlighted, yet they are not all connected by C-Links. The presence of the R-Links between components provides the boundary between C-Groups; one such boundary exists in the R-Links that separate the Canopy related components in the upper right from the Beam components in Figure 7.17. There are four C-Groups in the diagram, the Shaft Group, the Canopy Group, and two Beam Groups.

Application of the C-Group guideline to these four groups results in the effort flow diagrams shown in Figure 7.18, where eight nodes represent 36 components in various stages of evolution, less than half the initial number.

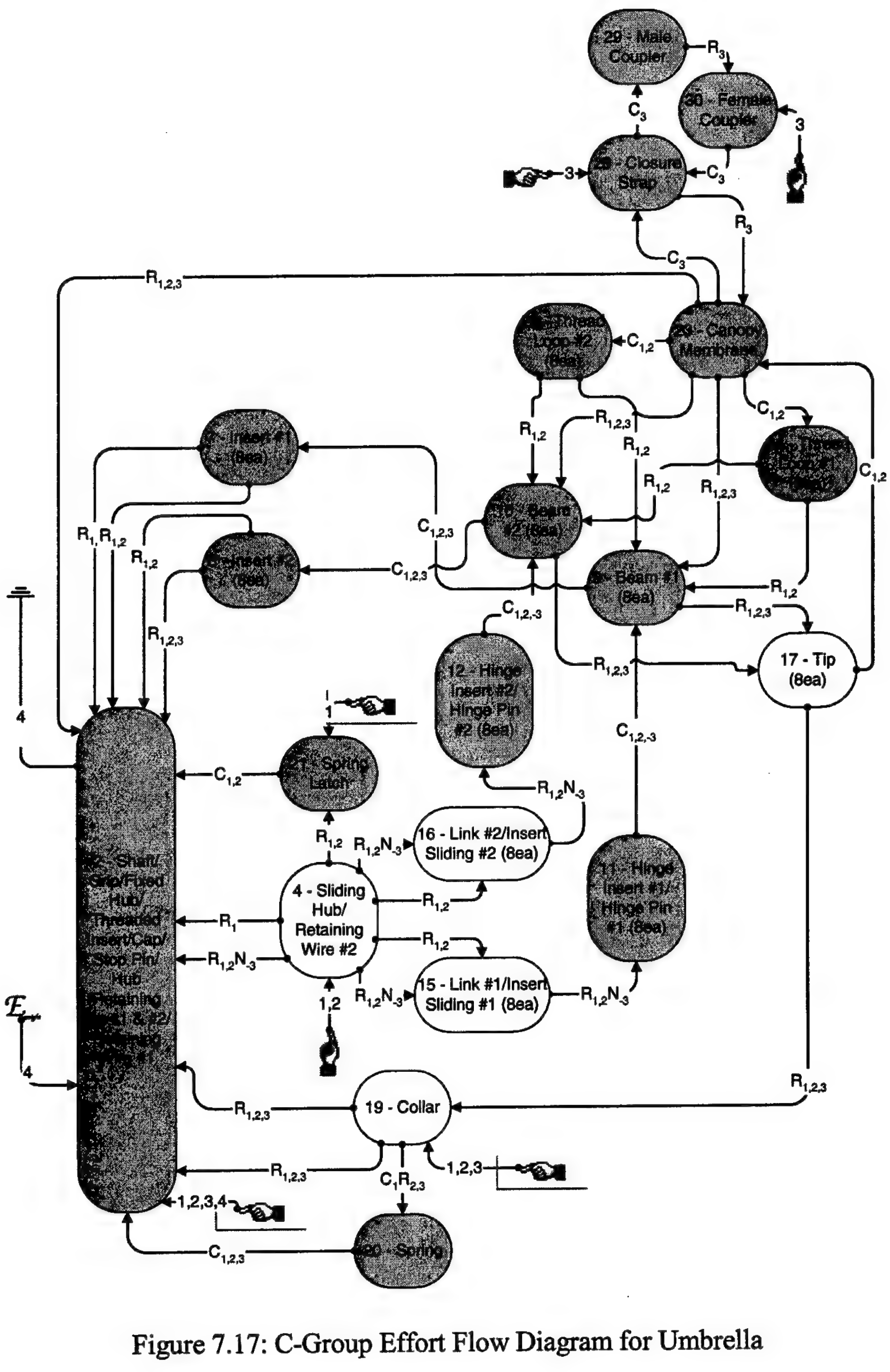


Figure 7.17: C-Group Effort Flow Diagram for Umbrella

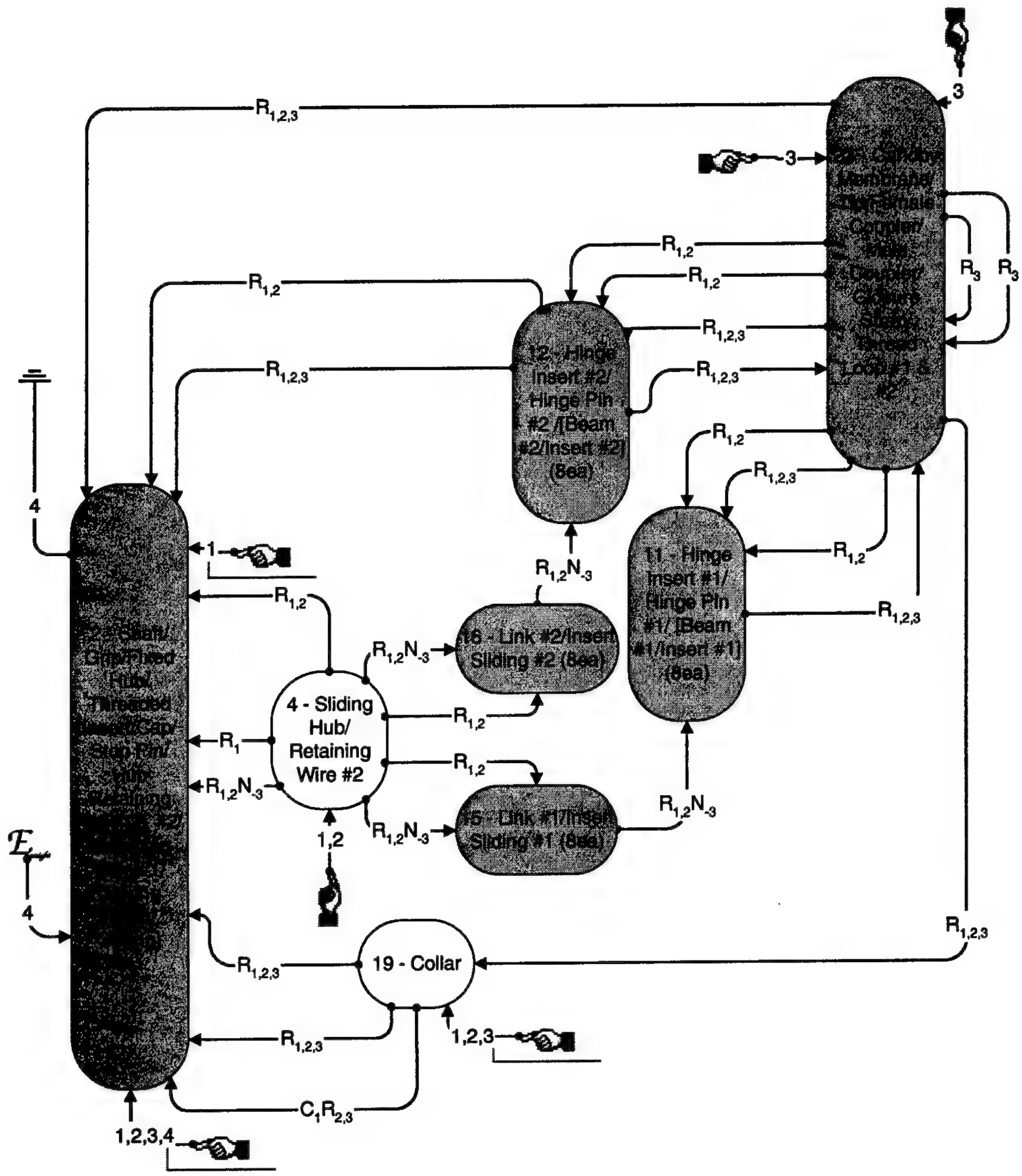


Figure 7.18: Post C-Group Contraction Effort Flow Diagram with Link Annotations

Having executed all the C-Group combination opportunities at once (Figure 7.18), the necessary conditions are checked for the combined components. Component 23, the Canopy is evaluated first. In the original product, the canopy is made from a synthetic textile, probably Nylon, and it is unlikely the Canopy can be made from a single

piece of material. Issues confounding a one-piece canopy are the closure strap and coupler, the tips, and the loops. The new Canopy component that results from component combination is therefore unlikely to be embodied in the final evolved product. Representation of the combined Canopy continues as a single node in the remaining analysis, but that single node now represents a module rather than a combined component.

Components 11 and 12 satisfy the necessary conditions, the deformable beam is made of steel, as are the insert and the hinge pin, the only apparent difficulty is manufacturability of an integral hinge pin. Possible solutions to this conflict include an integral attachment strategy (snap fit) for the interface between the link and the pin. Finally, the composition of the Shaft component has changed little from the 1st-order analysis phase, except for inclusion of the Spring, which seems to negate the possibility of constructing the Shaft from wood. Either a new material choice such as a polymer is required; or, the Spring component may be excluded from combination.

Referring to the collected guidelines leads to the Integral Attachment guideline, which is useful in combining the latch with the shaft. In addition, the Distribution of Compliance guideline is useful in generating concepts for combination of the Hinge, Insert, Pin and Beam. Since product revolution is the goal, design concept generation will be curtailed until after the Nth-order analysis, where the redesign effort reaches its full potential. At that point, the highest achievable level of evolution will be embodied in a product. For now, effort flow analysis continues with Nth-order analysis.

7.4.6.3 - Nth Order Analysis

The Nth-order analysis phase represents the furthest extent for product evolution with effort flow analysis. In this phase, the design guidelines with the highest potential for revolution, and for failure, are applied. Nth-order analysis (Figure 7.19) begins with the effort flow diagram of Figure 7.18, which is the result of 2nd-order analysis.

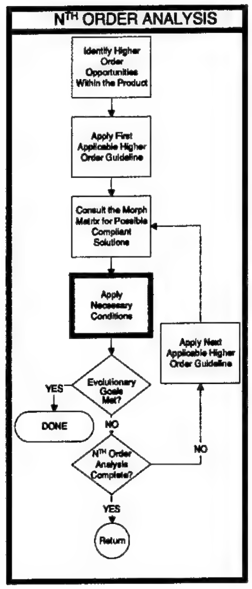


Figure 7.19: Nth-Order Analysis Process Chart

Nth-order analysis begins with the application of the following three guidelines to the umbrella product.

1. The RN-Link guideline is applied at the interfaces between the Links/Sliding Insert and the Hub and between the Links and the Hinges.
2. The 1-DOF R-Link guideline is applied at the interfaces between the Links/Sliding Insert and the Sliding Hub and between the Links and the Hinges; and
3. The Redundant Parallel Links guideline is applied to the two R-Links associated with the wire that act between the Sliding Hub and both of the Links/Sliding Insert.

Application of these three guidelines results in the diagram shown in Figure 7.20. The link labels are annotated to capture the original connectivity of the components, more on this in the Observations section. Three nodes remain in the diagram representing 10 components: the shaft, 8 arms, and the Canopy, where the Canopy module is treated as a single component.

Only four links remain between the new Arm component and the canopy, as a result of applying the Redundant Parallel Links guideline to remove the redundant links that resulted from contraction of the twin arms.

Application of the 1-DOF guideline to the Hub-and-Links group and to the Links-and-Hinges group results in a single compliant component that replaces the entire arm assembly. To embody this component, the Distribution of Compliance guideline is needed in conjunction with the Example Solutions. Combination of these components is confounding. The original Beam components use distributed compliance in the form of a bending beam, but combination at the pin joints implies that a localized compliant architecture will be necessary. The solution becomes apparent when these two conflicting architectures are taken together; resulting in a distributed compliance architecture for which a finite element based synthesis approach is most appropriate [36]. In lieu of this computationally intensive approach, a design-by-analogy approach using the sample solutions will be used to generate design concepts.

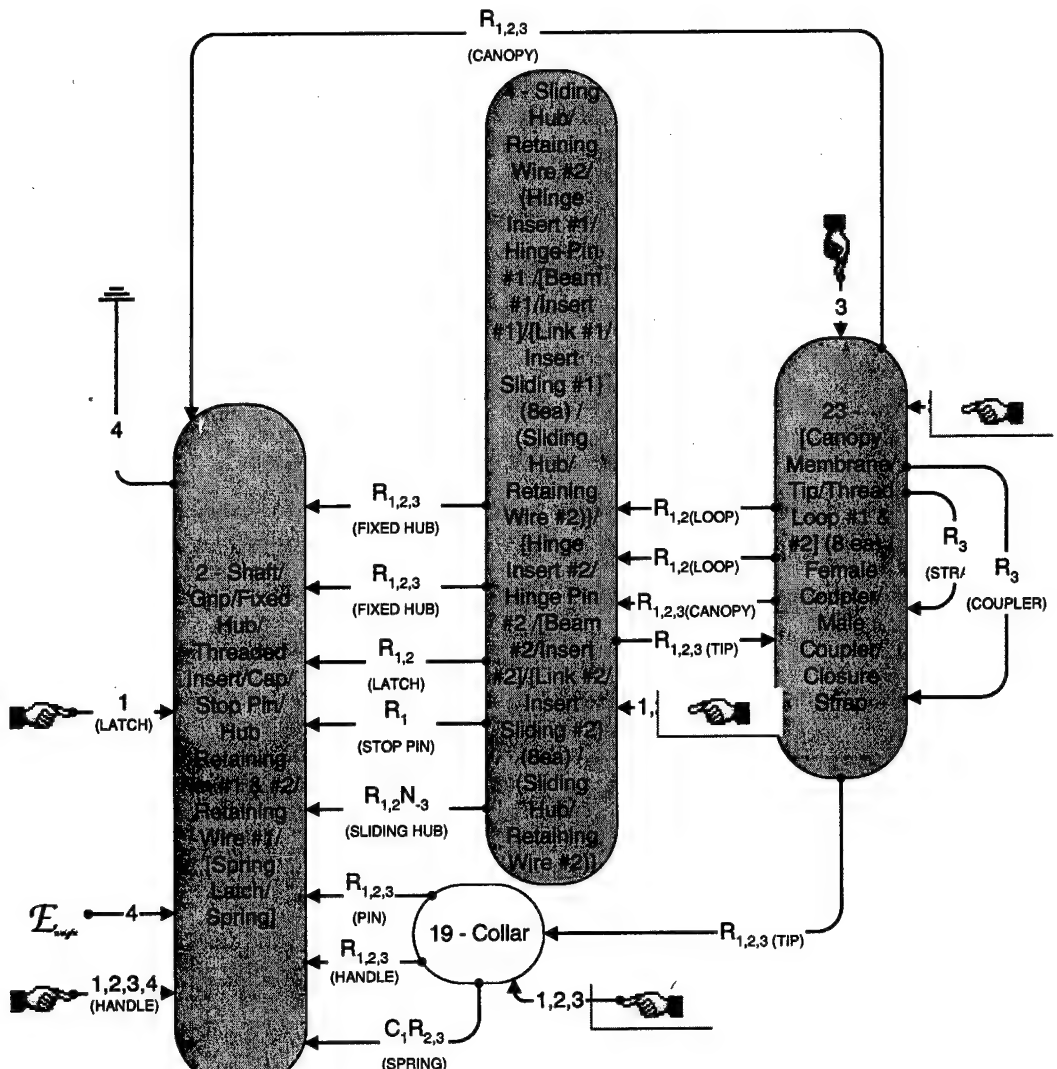


Figure 7.20: Result for First Application of Nth-Order Analysis, Diagram with Link Annotations

Reviewing the effort flow diagram of Figure 7.20 indicates that opportunities for product evolution remain. In particular, contraction across one or more of the links between the Hub and the Shaft is possible. To determine the feasibility of a combination at one of these interfaces, the parallel links between the Shaft and the Sliding Hub are evaluated for redundancy. According to the Redundant Parallel Links guideline, the links are relevant. In addition, according to the Large Motion R-Links guideline the R-Links

associated with the Latch, the Stop Pin, and the Sliding Hub are Large Motion R-Links and are the last opportunities to be considered. The R-Link associated with the Fixed Hub remain for consideration using the 1-DOF R-Link guideline, with the result being a compliant mechanism comprising the entire product except for the Collar and the Canopy as shown in Figure 7.21.

Notice the self-interfacing links attached to the Shaft in Figure 7.21, these represent instances where features of the combined components must maintain relative motion with the main component to provide some required behavior. Two of these self-interfacing links are associated with Human Interfaces, the Sliding Hub and the Latch both enable the Import Human Energy function in the product. These features have been integrated into the product, yet still require relative motion with some other feature in the component. These links will be maintained until they are determined to be relevant or not.

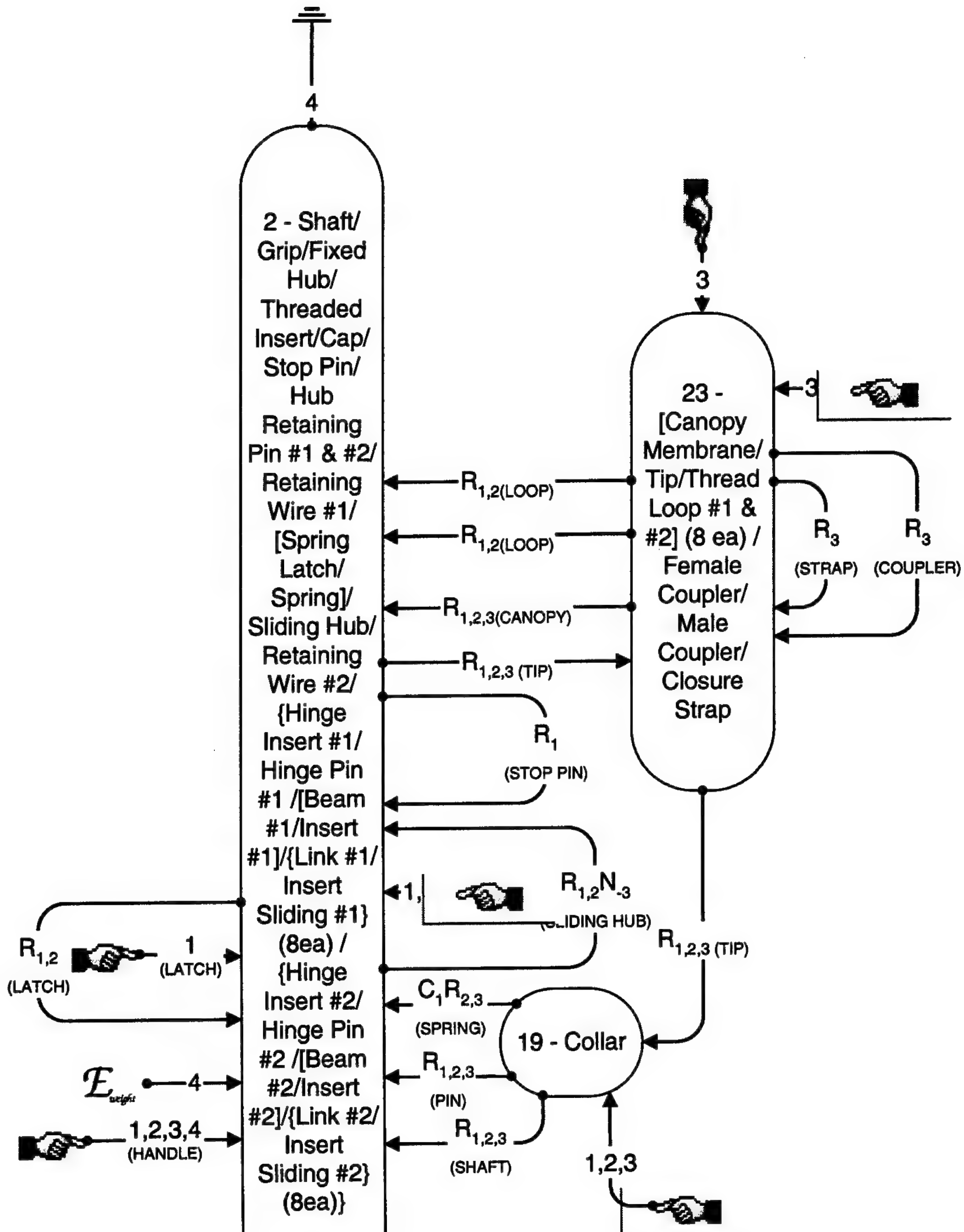


Figure 7.21: Intermediate Result of Nth-Order Analysis with Link Annotations

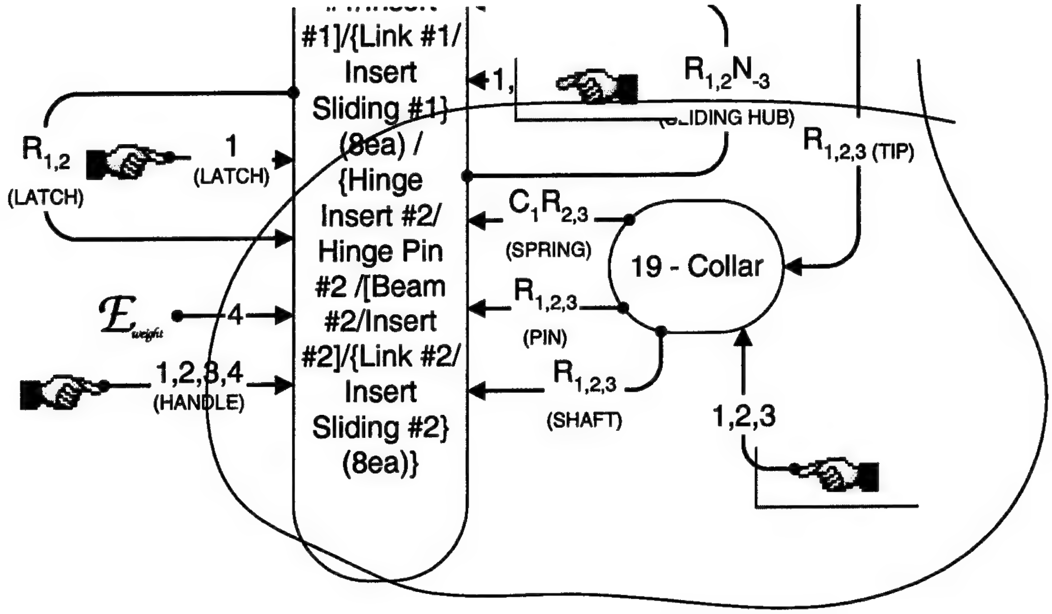


Figure 7.22: Collar Interfaces for Nth-Order Analysis

The only remaining links to be evaluated from Figure 7.21 are those associated with the Collar. This portion of the effort flow diagram is shown in Figure 7.22. The Tip to Collar interface requires the Large Motion R-Link guideline, meaning the components are virtually uncombinable. The parallel links associated with the Pin, Spring, and Shaft are evaluated next. Evaluation of the interaction between the Collar and the combined component across the Spring, Pin and Shaft interfaces indicates that contraction across the CR-Link will remove the need for the behavior provided by the pin. The pin provides a constraint function by limiting the travel of the collar along the shaft. With this insight in mind, the CR-Link is evaluated for removal.

Three possibilities exist for the CR-Link,:

1. The C-Link behavior dominates in the CR-Link and the Parallel R& C Links guideline can be used to combine the CR-Link with the parallel R-Links for the Shaft.
2. The R-Link behavior dominates and the structure can be treated as a parallel R-Link network.

3. The CR-Link can be treated by itself leaving the parallel R-Links initially untouched.

The Parallel R & C-Link guideline is applicable if the R-Link behavior in the CR-Link is assumed to be an unnecessary DOF in the operation of the product. Based on insight gained from operating the product, this assumption is deemed reasonable. Proper function of the collar does not require that it be free from the end of the spring. The R-Link motion captured in the CR-Link is a byproduct of manufacturing and material choices made for the product.

The Parallel R-Link guideline is not applicable in this case, as the specific scenarios described in that guideline are not evident in this product.

The CR-Link guideline is applicable here, resulting in combination across the CR-Link leaving two self-interfacing R_{123}-Links on the combined component.

The Choosing Between Contraction Options guideline is invoked to determine which of the two applicable guidelines to pursue. The Parallel R & C-Link guideline is chosen because it reduces the number of links that remain in the diagram. This approach also makes possible the removal of the R-Link associated with the Pin as discussed previously. The diagram that results is shown in Figure 7.23.

No further guidelines exist for N^{th}-order analysis, so the necessary conditions may now be applied to the product evolution opportunities identified for the umbrella product.

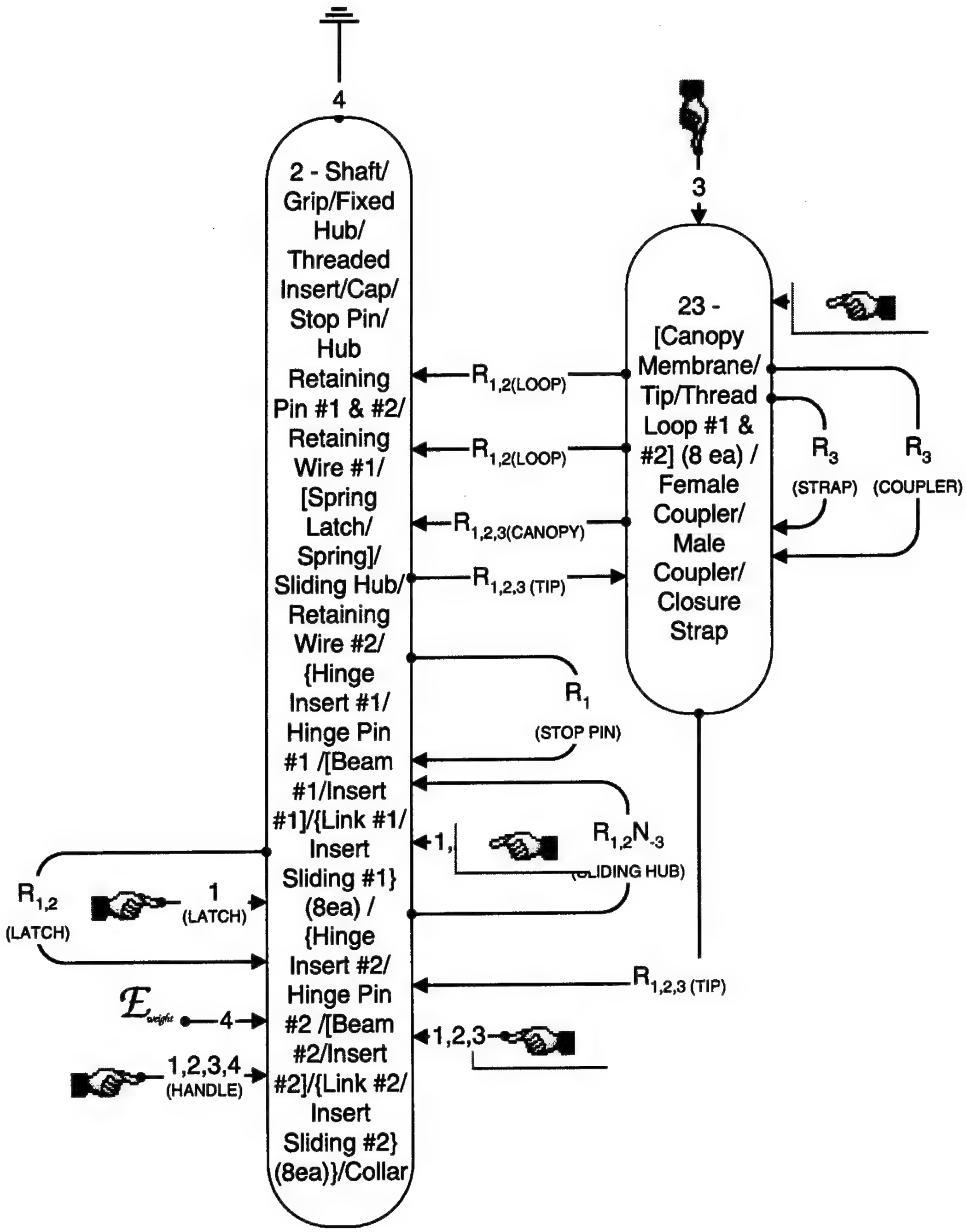


Figure 7.23: Final Result of Nth-Order Analysis with Link Annotations

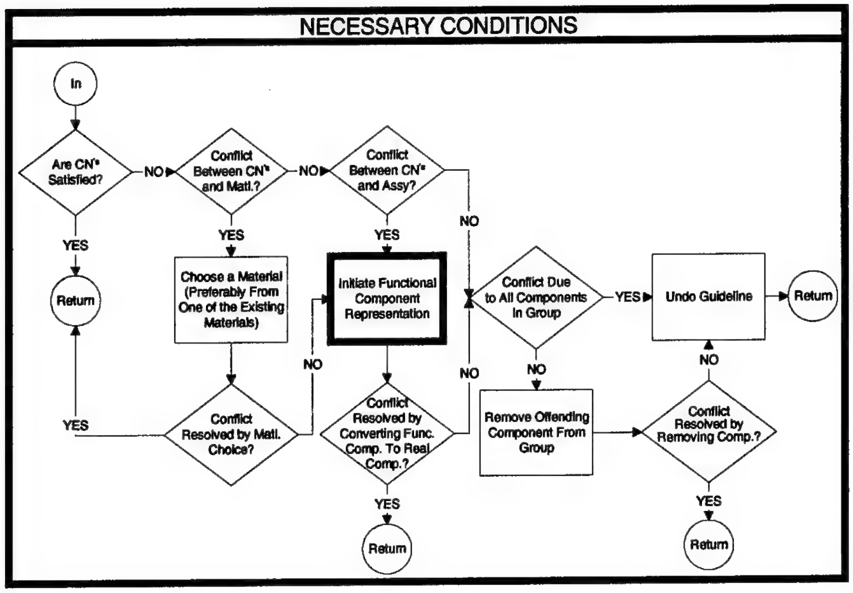


Figure 7.24: Necessary Conditions Process Chart

7.4.6.4 - Necessary Conditions

In order to Apply the necessary conditions, design concepts must be generated for the product evolution opportunities identified in effort flow analysis. Concept generation proceeds using the results of applying the design guidelines along with the original product and the example solutions from Chapter 5. Satisfaction of the Necessary Conditions implies that a design concept does not create material or assembly related conflicts with the CN's. Conflicts that arise during concept generation are settled using the process chart shown in Figure 7.24. The question remains, "How to embody the result of this effort flow analysis effort?"

7.5 - The Result

Using the effort flow diagram and the solution examples for the Small Motion R-Link and 1-DOF R-link guidelines as well as the original product as an example, a design concept is proposed. The solution uses both distributed compliance and localized compliance to embody the umbrella product as a monolithic structure covered by a canopy module. A solid model of the proposed structure is shown in Figure 7.25.

The functional prototype for the design concept uses four arm assemblies instead of the eight arms of the original. Each arm is connected to the fixed hub and the sliding hub using living hinges. The arm assemblies themselves consist of the original beam and link connected to one another by a living hinge. The beam is deformable with a variable cross-section that is thicker near the fixed hub and tapers down toward the free end. The variation in cross section promotes greater deflection near the free end while remaining relatively stiff at the fixed end. Design of the beam section exemplifies application of both the I vs Bending Stress guideline and the Distributed Compliance guideline.

The one-piece umbrella frame also applies the Use Bifurcation to Provide Locking guideline as it uses one of two stable states to maintain the locked open position. Locking is provided by an over-center arrangement for the Sliding Hub, Sliding Hub travel is limited by an integral stop in the Fixed Hub. A larger ¼ view of the Shaft, Sliding Hub, Fixed Hub, and Arm assembly is shown in Figure 7.26. A detailed view of the sliding hub and living hinges is provided in Figure 7.27.

The design uses a monolithic structure intended for proof of concept and functional prototyping. Clearly, difficulties with manufacturing a one-piece assembly like this are many, but by using the Selective Laser Sintering (SLS) process the complex geometry is built as a one-piece structure. A production version would require a faster manufacturing process that in turn might dictate the inclusion of more components in the design.

Figure 7.25: Rendering of Solid Model for One-Piece Umbrella Structure

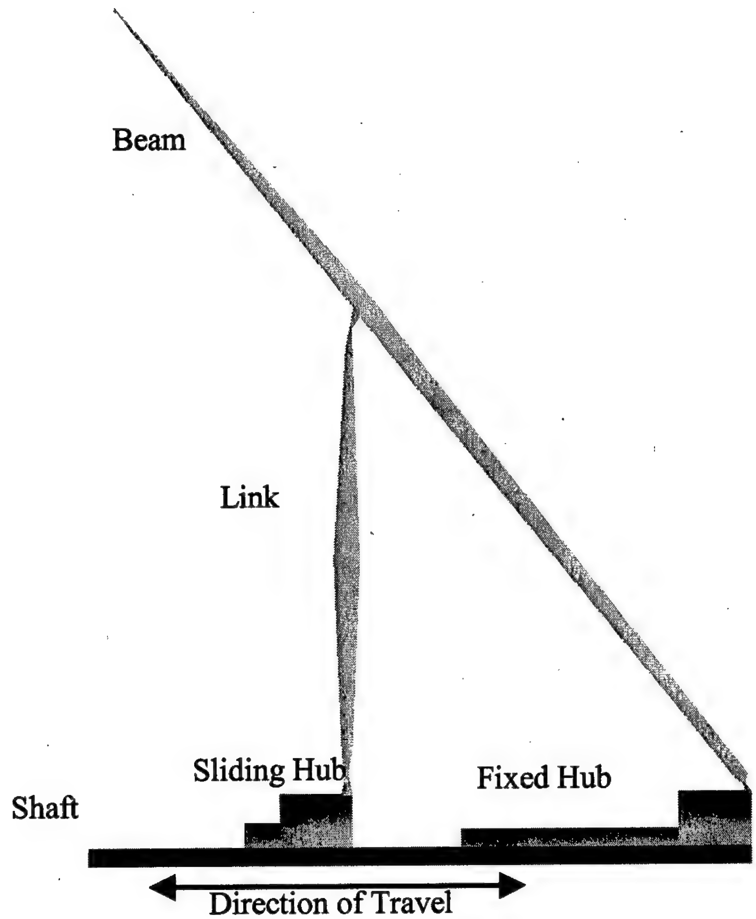


Figure 7.26: Side View of Arm, Sliding Hub, Link, and Fixed Hub Portions of Umbrella

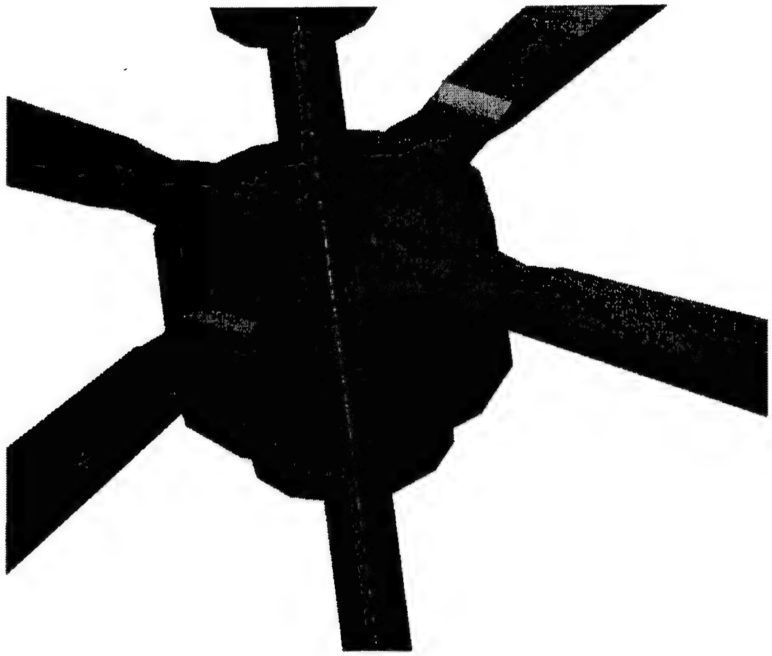


Figure 7.27: Detail View of Living Hinges Connecting Sliding Hub and Links

7.5.1 - Design Concept Analysis

Excerpts from the finite element analysis report for the monolithic umbrella are presented in the following paragraphs [164].

Most of the umbrella sustained negligible stress except for the living hinges. As expected, the living hinges had the highest stress, with the maximum stress reaching 61 MPa. This exceeds the assumed ultimate stress of the material, but these areas were nearly invisible in the model indicating thin lines or small points. There were slightly larger areas that exceeded the yield stress of 40 MPa, but again, they were very small. Figure 7.28 and Figure 7.29 show the best views of these results.

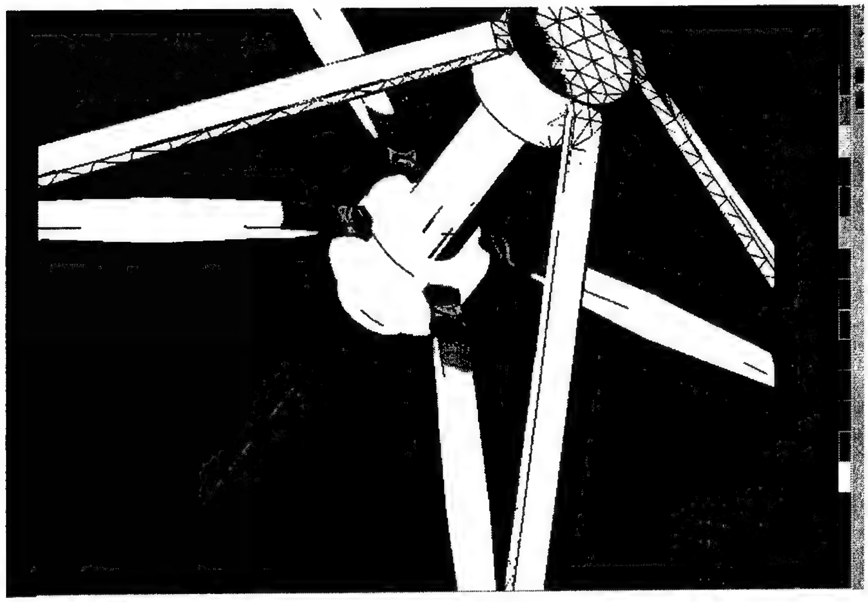


Figure 7.28: Results Near Sliding Hub

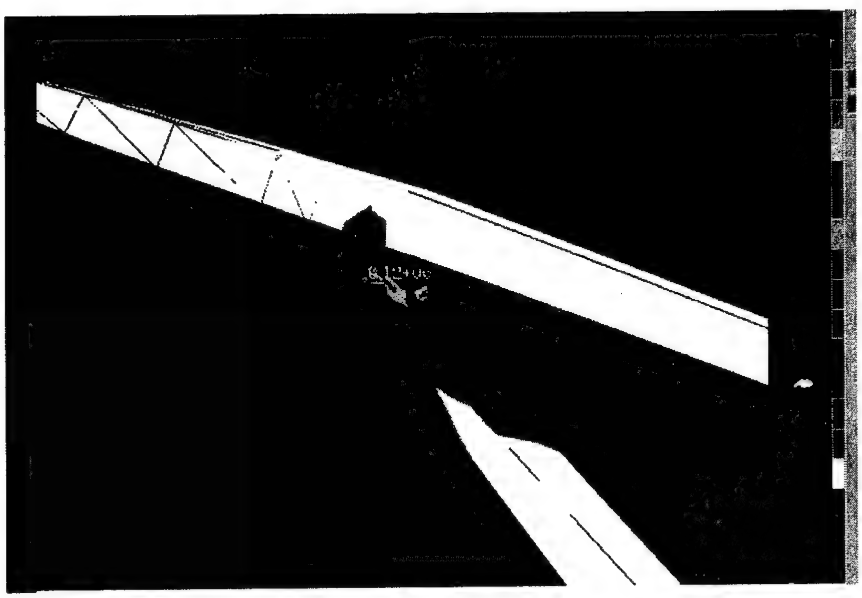


Figure 7.29: Results for Living Hinge between Link and Beam

Accurate analytical results to corroborate the model results are impossible due to the extremely complex geometry, stress concentrations, and loading. In the opinion of the analyst, if analytical results were found, they would likely prove inaccurate.

However, a sanity check of the results is done by noting that the stress values are the same order of magnitude as the yield and ultimate stresses, and are thus deemed reasonable.

Sources of error include the possibility of incorrect material properties. Additionally, finite element models are stiffer in general than exact models, and may cause problems with a structure designed to be flexible. Another possible source of error arises from moving the Sliding Hub 4 centimeters along the Shaft, which may violate the small displacement assumption.

These results indicate a possibility that the umbrella could break or develop cracks using the current geometry, especially when factors such as wind and rain loading are considered [164].

A source of error not noted by the analyst is that the material properties used for the model do not account for the visco-elastic properties inherent in polymer materials. The other material properties used in the model were for Nylon, and the finite element model used a linear elastic material model. Hence, these finite element modeling results are suspect in any prediction of failure due to high stresses.

7.5.2 - Alternate Concepts

7.5.2.1 - 8-Piece Frame

An alternative concept to the monolithic frame is the 8-piece frame design developed as a partially compliant umbrella structure. The 8-piece frame shown in Figure 7.30 is based on the effort flow diagram of Figure 7.20, where the arms are maintained as separate compliant components. This design concept takes into consideration the manufacturing difficulty of the one-piece design by allowing the arm assemblies (Figure 7.31) to be manufactured separately from the shaft. The 8-piece design is again a functional prototype constructed using the SLS process. In the prototype, the arms are fully captured in the hubs, a production version would be assembled using an integral attachment strategy between these components.

Figure 7.30: 8-Piece Design Variant for Umbrella Structure

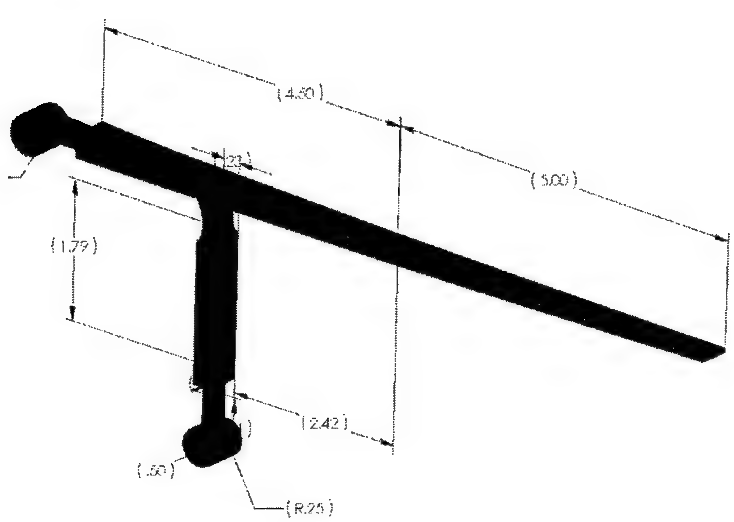


Figure 7.31: Arm Detail for 8-Piece Umbrella Structure

7.5.2.2 - Other Concepts

In addition to the design concepts generated using effort flow analysis; a brainstorming exercise was conducted with a group of engineers. The goal of this exercise is to generate concepts for a "compliant umbrella." Several of the results are presented in the Figure 7.32 through Figure 7.34. Each concept has similar themes to those generated using effort flow analysis. The point of including these examples is the credence they lend to the idea that effort flow analysis functions as a concept generation engine. These examples demonstrate that the systematic approach directs a single designer toward solutions that might happen by chance in an ad hoc approach, or that may be produced through the application of more traditional concept generation techniques.

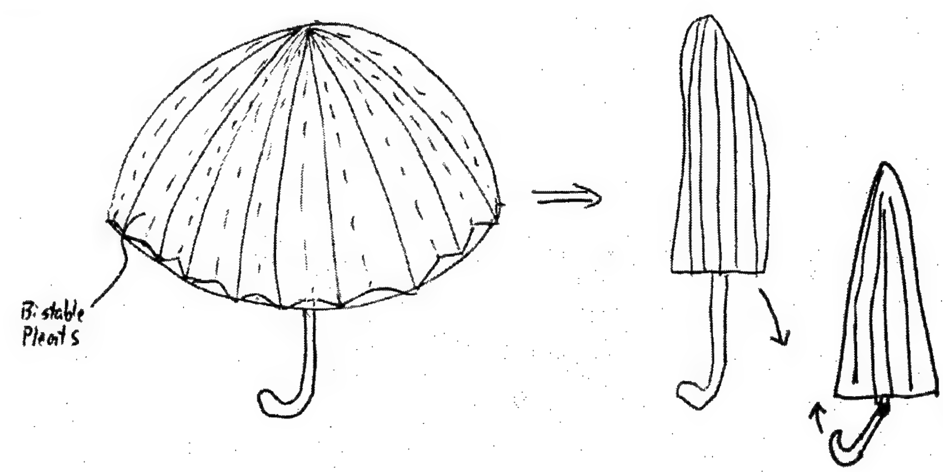


Figure 7.32: Bistable Pleats Umbrella Concept

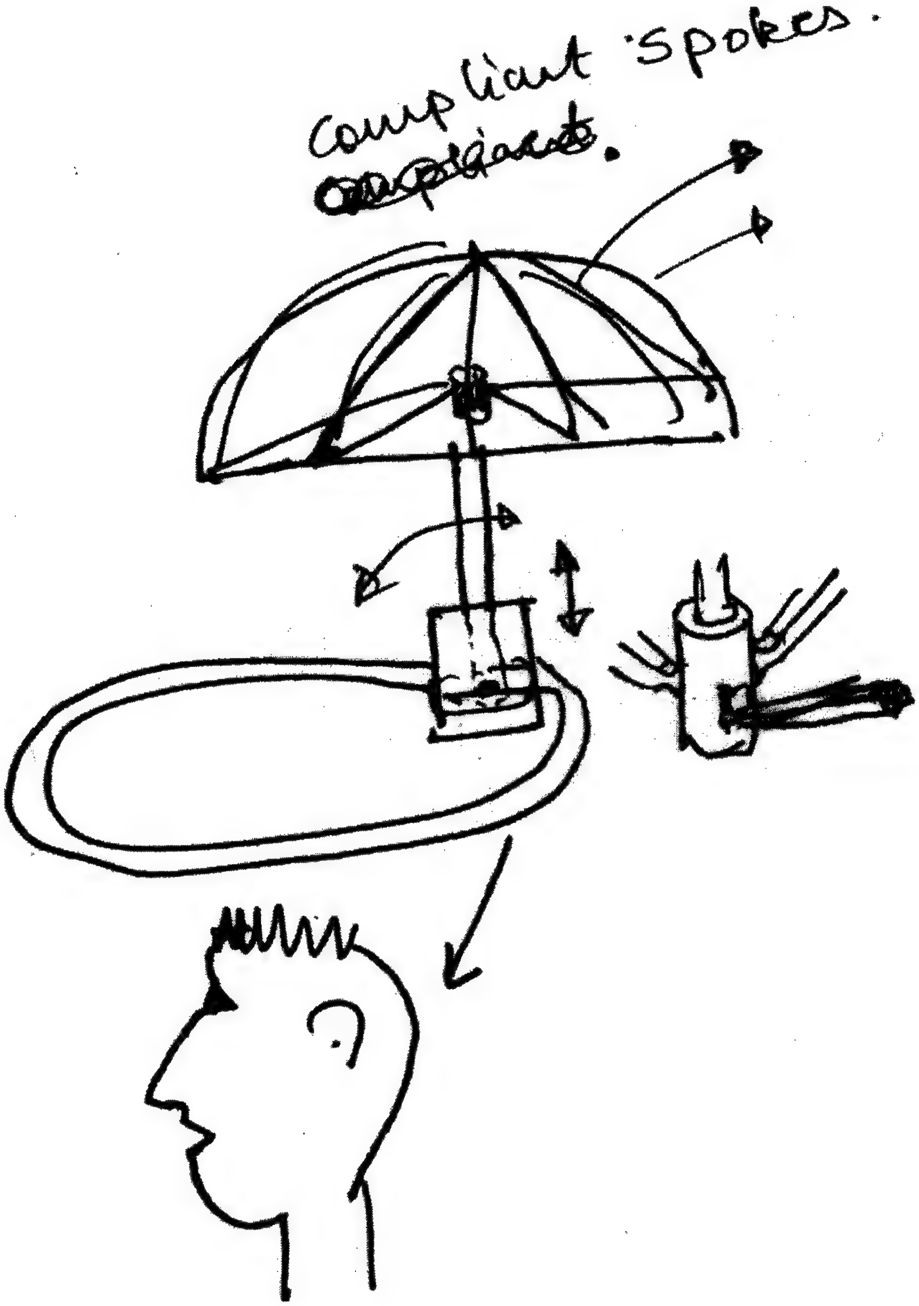


Figure 7.33: The "Hatbrella" with Compliant Spokes and Living Hinges

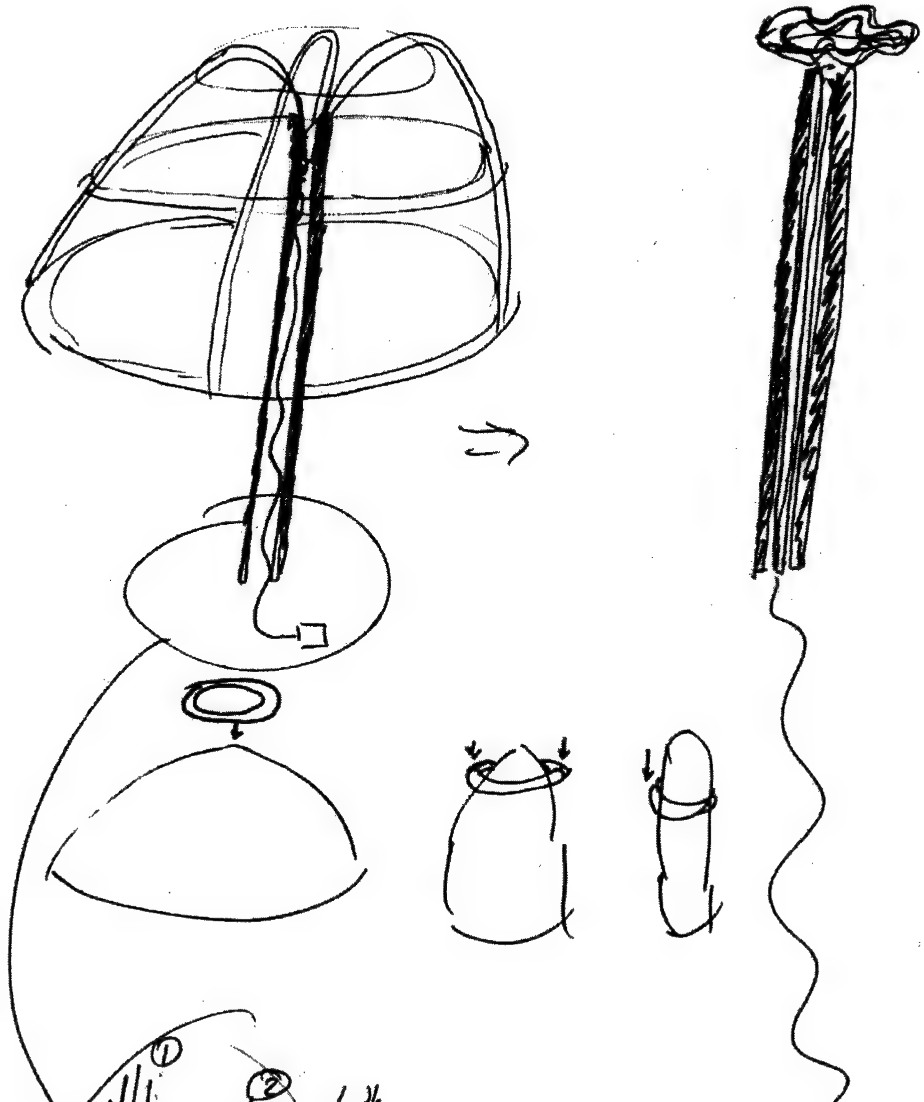


Figure 7.34: The "Palm Tree" with Compliant Limbs and Shape Memory

7.6 - OBSERVATIONS

In the case of the one-piece frame, the product evolution is quite dramatic, the product is revolutionary in its concept, albeit difficult to manufacture. The 8-Piece frame, although less revolutionary is a significant improvement over the original artifact. From a part count perspective, the improvement is substantial. Excluding the 28 parts associated with the canopy, the original product used 120 components to create the structure of the umbrella frame. The two evolved products provide the same functions using one and seven parts respectively. Granted, these are not production units, and some growth in the number of components could be expected as the design is realized for production, but it is unlikely that the increase would approach the ten-fold increase necessary to return to the previous levels.

One of the difficulties encountered in redesigning the umbrella frame is designing the living hinges, especially when using the SLS process for prototype construction. Considerable care must be exercised to ensure the hinges are built in a part bed orientation that ensures the build direction is parallel to the rotation axis of the hinge. Other orientations lead to immediate rupture failure in the scan plane of the hinge material.

In effort flow diagrams representing an evolved product, the origins of the links is clouded by component combination; to improve clarity, the diagram can be modified like the Post C-Group Contraction diagram of Figure 7.18, where additional information is added to the link labels to assist in understanding the relationships between the original components and the remaining links. The added information helps in determining if a link is still relevant, and in determining the features with which it is associated. Examples of links where the original connectivity is vague are the self-interfacing links attached to the Canopy module.

Self-interfacing links occur when a monolithic component has an interface with itself. For example, if the canopy was monolithic, and the closure strap remained as a feature of the canopy, the strap would wrap around the canopy to lock the umbrella closed. In doing so, the strap feature of the monolithic canopy would have a distributed R-Link interface with a circumferential region of the closed canopy. This type of

interaction is relatively common, and is represented as a self-interfacing link of the type shown on the Canopy module.

Overall, the result of this design exercise is a successful prototype that demonstrates the power of the effort flow analysis method as both an analysis tool and as a concept generation engine. A fitting end...

Chapter 8 - Conclusions and Future Pursuits

This dissertation presents the development and implementation of effort flow analysis, a design methodology for directed product evolution with a focus on the systematic incorporation of compliant mechanisms in the evolutionary process. Development of the methodology is motivated by the observation that the current industry approach to product evolution is predominantly ad hoc as are the methods for incorporating compliant mechanisms in product redesign.

8.1 - SUMMARY

The current state of design science in the area of compliant mechanism design is wide open for research and advancement. The field is especially open to innovation with methods that promote the incorporation of compliant mechanisms into existing mechanical artifacts. A brief survey of leading researchers from the field compliant mechanisms design and synthesis revealed that none of the parties had a systematic product evolution methodology to focus their efforts. The predominant response was that products were selected based on intuition and experience. A sample survey response from Prof Ashok Midha is included to illustrate the point. Two survey questions were posed:

1. How do you go about identifying the products in which you will use compliance as a solution?

> One potential category is when in the task prescription, force/torque-deflection or energy-deflection requirements are made. In other words, energy management is called for which takes the form of requiring certain force-or torque-deflection behavior in actuation of the mechanism. Or, it may simply be a matter of potential energy storage with displacement, as in a hand tool with a return spring.
>
> Another motivator may be a desire to reduce the number of parts for ease of manufacturing and/or assembly. Energy storage may be another requirement. This would work well in this methodology. If energy is not a concern, and only kinematics is, then the concern would be to minimize the energy storage in carefully designing the compliant mechanism. The benefit could still be in the manufacturing and assembly aspects.

> Some mechanisms may be injection molded. This limits the possible designs to strengths derived typically from the materials with which the part may be made. The significant benefits again are due to fewer pieces, and manufacturing and assembly aspects. If more complex compliant mechanisms are created using spring steel flexural segments, say, then clearly <u>the benefits are limited to higher magnitudes and precision of force/torque/energy requirements</u>, and some other properties, e.g. no clearances, lash or need for lubrication, etc.
> *2. Is your approach to this decision systematic, or intuitive?*
>
> I would say <u>"intuitive"</u>; <u>**no design methodology currently exists**</u> for making such decisions. There may be an opportunity to formalize the above thoughts and others. [165](emphasis added by author)

The above correspondence illustrates the general tenor of the survey responses received, the full text of which are contained in Appendix E. The response to the second question is especially encouraging. In each case, the response to the approach question indicated an intuitive approach to seeking compliant mechanism opportunities. This is exactly the reason that research in this field is so wide open. The claim here is not that rules for using compliant mechanisms are not available; the rules of thumb exist in trade manuals and books. The common element missing from each of these sources is the overall approach to concept generation for compliant mechanism design. The effort flow analysis methodology is developed to meet the need for a compliant mechanism concept generator.

Effort flow analysis is framed in design science, and maps directly to the six steps for design problem solving of Pahl and Beitz [49]. The research is carried out with an eye toward ultimately reaching industrial implementation. In fact, aspects of the method are in practice with design engineers in companies across the country. Such is the advantage of presenting research results in the near real time using the classroom as a forum.

The overall process of effort flow analysis begins at the project management level with the decision to pursue either an evolutionary or revolutionary redesign effort. Evolution is an incremental and steady march along the product evolution S-curve toward an evolved product capable of providing steady rates of return on the investments that are made in plant and equipment. Revolution, on the other hand, exemplifies a desire to make a jump to a new S-curve, jumping past the competition to a new level of product

performance. Products that create these jumps are know as disruptive technologies, and can result in rich rewards to the companies that have the capability to execute them. The difficulty is finding those opportunities; waiting for an opportunity to "walk through the door" is generally not an option. Effort flow analysis claims to be a method that is capable of actively pursuing product revolution opportunities.

Once the evolution/revolution decision is made, the methodology relies on its foundation in design science to proceed. The next steps involve experiencing and observing the product in operation and gathering customer needs, followed by product modeling that includes both activity diagrams and function structures. The results of these efforts are a set of customer needs and a set of user operations, which are the driving factors in effort flow analysis.

The customer needs provide the input output relationships for functional modeling, which in turn provides the necessary conditions criteria for determining whether a component combination opportunity is successful. The user operations determine the extent to which the product will be modeled, and ultimately which components will be considered for combination. The effort flow analysis modeling is accomplished using a semantic network known as an effort flow diagram.

The effort flow diagram is an abstract representation of the product that captures the components and their connectivity in an organic form. The effort flow diagram is essentially a collection of interconnected free-body diagrams that are distilled down to their essence. All that remains of the FBD's is the body and the forces and moments of interaction. The effort flow diagram contains no magnitude, direction, geometry, or material information. The bodies are represented as nodes, and the forces of interaction are represented as links between the nodes.

Using principles from physical systems modeling, the component connectivity of the links is further developed to capture the relative motion behavior that is present at the component interfaces. A basis set for relative motion in effort flow analysis is developed to allow characterization of the various types of relative motion observed in component interfaces. The result is a set of four orthogonal link types that represent the possible permutations of relative motion between mechanical components. The naming convention adopted to describe these link types is contained in Table 8.1.

Table 8.1: Table of Relative Motion Permutations

Link Type	Relative Motion Location	
	Between Interfaces	Between Components
N-Link	0	0
C-Link	0	1
R-Link	1	1
I-Link	1	0

Effort Flow Analysis Link Types

The four flow links are defined as follows:

"N-Link": No relative motion between components.

"C-Link": Relative motion between the non-interfacial regions of components.

"R-Link": Relative motion at the interface and between other regions.

"I-Link": Relative motion at the interface only. (It should be noted that this type of interface has not been observed in any device from the mechanical domain, but is included in the basis set for completeness.)

These links are used to model the interaction between components in the effort flow diagram. Depending on the link formations that arise in the model, various component combination opportunities are identified. These opportunities are identified based on a set of product evolution design guidelines, most of which are developed in this dissertation.

The focus of the guideline development effort is an empirical study that analyzes 16 product groups totaling 49 individual products, each having very specific characteristics. The characteristics of interest for the products of the study are:

(i) that it be from the mechanical domain;

(ii) that it use relative motion functions in its operation;

(iii) that one product exist in the group that is not significantly compliant in it construction; and finally,

(iv) that one or more products exist in the group that use some form of compliant mechanism to provide the relative motion functions.

The results of the empirical study are a set of 29 design guidelines divided into five domains: Relative Motion, Graph Structure, Functional, Analysis, and Necessary Conditions. The domain lexicon is devised to aid the designer in accessing the appropriate guideline for the situation at hand. In addition, many of the guidelines have one or more sample solutions associated with them. These sample solutions are meant to provide the seeds for design concepts using the design-by-analogy approach.

The accuracy with which the overall methodology represents real products in the hands of real engineers is assessed using an academic exercise. 17 graduate level engineers are tasked with applying the effort flow analysis methodology to the evolution of two products. The products are chosen for their relative simplicity and for the existence of a known evolved solution to compare the results to. The outcome is encouraging, as 94% of the subjects were able to identify and act on opportunities associated with the fundamental guidelines, and the average part count reduction in the products was within one standard deviation of the expected result. The only discouraging result from the study was the accuracy with which the subjects were able to characterize the relative motion in the links. The reliability of this result is degraded to some degree by the difficulty in accounting for the modeling decisions made by the subjects.

Finally, effort flow analysis is applied to a product that does not have a know evolutionary result. The goal is to demonstrate the power of the method to take a product from the mechanical domain and systematically evolve the artifact by incorporating compliant mechanisms into its design. In this case, the product is a golf umbrella. The original part count is 123 components. The result is a functional prototype that consists of a single monolithic frame structure supporting a traditional canopy made from textile material comprising a total of 12 components. The part count reduction is dramatic.

8.2 - CONTRIBUTIONS

The contributions of this dissertation lie in the original development of a design methodology for directed product evolution .

8.2.1 - Theoretical Foundation for Method

The first contribution of this dissertation is in the development of a solid theoretical foundation for the effort flow analysis methodology. According to Antonsson [48], for a design method or tool to be considered a legitimate product of engineering design research, it must be based on a rigorous theoretical foundation. The predecessor of effort flow analysis, force flow analysis, is a methodology based on the intuition and experience of its developer. Since the development was intuitive in nature, it lacked the depth required by Antonsson's standard. Hence, in order for effort flow analysis to be considered legitimate in the light of this standard, the onus of building a rigorous foundation falls squarely on the shoulders of this dissertation.

The result is a design methodology that takes its analytic strength from the theory of mechanics and its representational strength from the theory of graphs. These two fundamental theories are brought together with tenets from physical systems modeling to produce a product modeling and analysis tool that is robust enough to model virtually any product from the mechanical domain.

An addition benefit of a strong theoretical foundation is that it allows the method to evolve to new application areas that are supported by the same theories on which the method is based. Methods that are intuitive or ad hoc in nature are limited to the experience base of the user or their mentor, do not enjoy the benefit of a broad foundation such as the theory of mechanics to support significant modification and extension.

8.2.2 - Methodology

The second, and arguably the most significant, contribution of this dissertation is the overall methodology of effort flow analysis. The methodology is completely new in the field of compliant mechanism synthesis and design. The literature is essentially devoid of references for design methods with a broad enough scope to take traditionally rigid body architectures through a systematic directed evolution to a compliant architecture. This is the most significant contribution of effort flow analysis to the artifact theory for compliant mechanisms.

One of the stated objectives of this dissertation was to create a methodology that presents a reliable, repeatable, and accurate representation of mechanical products.

The reliability of the method is enhanced by a system of checks and balances built into the necessary conditions algorithm of the effort flow analysis methodology. The necessary conditions are based on laws of mechanics and the functional requirements that drive product design. The necessary conditions are designed to use the fundamental theories to prevent a designer from pursuing unattainable design concepts while still allowing the generation of novel design concepts that lead to the creation of previously unknown solutions to problems in the mechanical domain. The reliability of the method is also enhanced by the fact that Mechanics and Graph Theory are well established fields with strong ties to the mechanical domain, hence the application of effort flow analysis to the redesign of artifacts within this domain is well supported by those theories.

The repeatability of effort flow analysis as a product modeling and evolution method is demonstrated by the results of the repeatability study. The subjects were able to model the component interfaces with accuracy of 92%, the standard deviation for the staple remover was 1.75 out of 12 possible interfaces, while the standard deviation for the pen was 0.61 out of 13 possible interfaces, see Table 8.2 for a summary of the results.

The subject's ability to reproduce the standard improved between the two products. The pen product is arguably more complex than the staple remover, so the experience gained with staple remover seems to have improved the repeatability of the method. This is consistent with learning models that suggest a first attempt at an activity by a student is less successful than subsequent attempts [166]. For this reason, it is claimed that the pen results are more representative of an experienced practitioner than are the staple remover. Similar results are observed in the product evolution data, where the subjects were able to achieve the expected number of components to within less than one standard deviation in both cases, see Table 8.2 for a summary of the results.

Table 8.2: Repeatability and Product Evolution Results for Staple Remover and Pen

Product	Number of Internal Interfaces	Avg. Result	Std Dev
Staple Remover	11	11.1	1.75
Pen	13	12	0.61
	Number of Evolved Comp		
Staple Remover	2	1.53	1.07
Pen	5	4.17	1.29

Accuracy is measured by how closely a measurement is to the true value of the quantity measured. The accuracy of this method is determined by calculating the ratio of the Result to the Standard. The subjects were able to reproduce the standard number of component interfaces with an accuracy of 93% and 92% for the staple remover and the pen respectively, and were able to reproduce the expected number of evolved components with an accuracy of 77% and 83% for the staple remover and the pen respectively. The identification of interfaces is expected to produce better results than the more involved and subjective process of generating design concepts, which is born out in this study.

The only aspect of modeling the product that did not produce the desired results is the characterization of relative motion at the interfaces. The factors that contributed to these results are many, some are based in the methodology itself, and others are based in the way the methodology was presented. In addition, due to the human agent acting in the design process, there is some variation in the link characterization. Much of the variation rests on the practitioner's decision about the relative importance of the flow in question. Correction of this issue creates a conflict with the efficacy of the method as a concept generation engine. In order to drive the interface characterization results toward the standard, the method must become more algorithmic, which seems to conflict with the creative aspects inherent in design.

8.2.3 - Guidelines

The third contribution of this dissertation is the creation of an approach to systematically incorporate the synthesis of compliant solutions in product redesign. The

source of this contribution is the set of product evolution design guidelines that result from the empirical product study.

According to Antonsson, design method development should strive to establish a substantial base of empirical observations to support broad application of the method [48]. In the case of the effort flow analysis method, the empirical base consists of 16 product groups composed of 49 separate products. The result is a set of 29 design guidelines that foster the synthesis of compliant solutions in product redesign.

One of the strengths of artifact theories in general, and effort flow analysis in particular, is the potential for the method to evolve through continued growth in the store of captured design knowledge. The strong theoretical foundation of effort flow analysis coupled with the empirical basis established thus far provides a structure into which knowledge for compliant mechanism design can be deposited.

8.2.4 - Example Solutions

The fourth contribution of this dissertation is the creation of a matrix of example solutions that facilitates design-by-analogy by providing solution examples that are cataloged based on the guideline that leads to their solution. In essence, this cataloging maps the present state of the components to possible combined or compliant solutions using the design guidelines as a linkage. By identifying a guideline that is applicable to the current situation, analogous solutions can be found that demonstrate one or more instances of potential final states. The framework for this contribution has been fully established, but the catalog is not fully populated.

Increasing the population of the catalog remains an issue for future work in effort flow analysis. Again, this is an example of the power of artifact theories to continue to evolve when new and useful design knowledge becomes available.

8.2.5 - Personal Invention

The fifth and final contribution of this dissertation is the creation of an evolved version of the umbrella that uses compliant mechanisms in place of links and revolute joints. The results speak for themselves, or, the proof is in the product. The prototype

that resulted from fully applying effort flow analysis to the redesign of a golf umbrella is a dramatic departure from traditional designs for umbrellas.

The real contribution of the invention is the proof of concept that it provides for the methodology. The physical artifact validates the theory that part count and complexity can be reduced through the systematic application of directed product evolution methods. When those methods are properly applied to an evolvable product, the results may be a revolutionary transformation from the traditional rigid body architecture to a partially or fully compliant architecture.

8.3 - Research Opportunities

The work presented in this dissertation opens the door to several research opportunities.

8.3.1 - Further Guidelines & Solution Examples

The first of the opportunities is the continued search for new design guidelines and solution examples. The fact that there is continued interest in gathering design knowledge should not detract from the work done thus far, as there are no claims that all the guidelines for directed product evolution have been found. In fact, the extension of the methodology to energy domains beyond the mechanical domain is a very promising area. It is well known from systems modeling using power methods that effort and flow are required to make power. From that combination, it is hypothesized that effort flow is an analysis tool for identifying product evolution opportunities in the other energy domains as well. The crux of the issue is to identify the flow related markers, relative motion in the mechanical domain, that allow the designer to identify the opportunities captured in the model. The goal of exploring other domains is to develop a more general theory of product evolution through the collection and storage of design knowledge.

One school of thought on the collection of design knowledge is that as knowledge is gathered, that knowledge continues to fill voids in the design theory until ultimately a mosaic of system specific design theories coalesces to reveal generalizations that lead a global design theory [55]. Since no global theory yet exists for design science, it follows from the mosaic analogy that there are still pieces of knowledge to be

gathered. Each piece of knowledge that is captured, through methods such as effort flow analysis, contributes to moving design science toward a global design theory. This concept is captured in Figure 8.1.

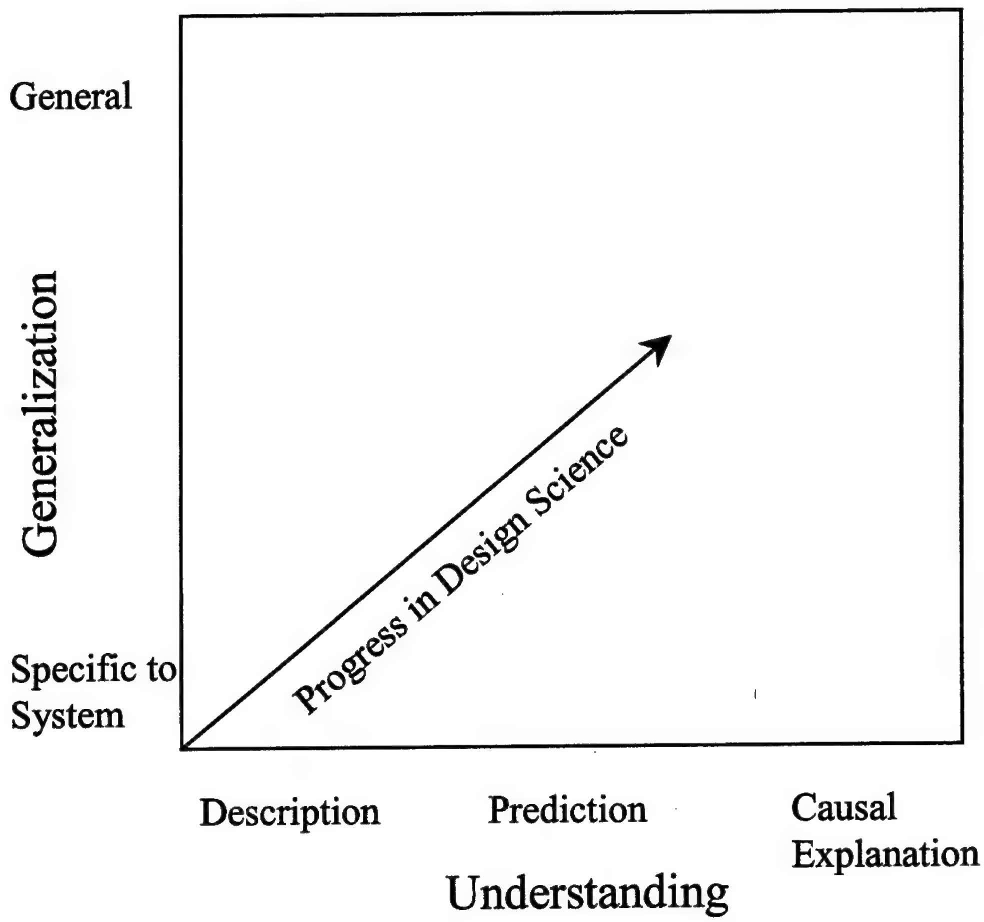


Figure 8.1: Space of Research Questions [167]

8.3.2 - Component Naming Basis

One result of developing the representation scheme for components in effort flow analysis is a need for a standard set of component names. This standard set of names is needed to aid in the capture and storage of design knowledge for specific products and classes of products. For example, a functional model is used to identify product function and a bill of materials documents the components. Using these two sets of data,

components can be related to the function(s) they provide. A positive consequence of recording this component-function knowledge over many products is the formation of a repository of design knowledge.

Another application for a standard set of component names is in the area of communication of design information. Often different methods are employed in categorizing components, and the use of natural language is ambiguous in its interpretation among different designers. These issues make design communication difficult among different sections of the same organization or even among individuals. Researchers have previously sought to standardize a function vocabulary and failure mode concepts [98, 168] but there has been little effort to construct a standardized component basis. Establishing uniformity and consistency in the representation of components will improve designer communication within and between organizations.

8.3.3 - Function to Component Matrix

An opportunity for future research that became apparent during the development of effort flow analysis is the concept of a Function to Component matrix, which is related to the component-naming basis just discussed. The establishment of a component-naming basis used in conjunction with the functional basis [54] facilitates the construction of a function-component matrix that is used as a preliminary version of a concept generation tool [169, 170]. The function-component matrix forms a relationship between components and their functions for a product where the components determine the columns of the matrix and the functions determine the rows. The matrix elements contain a zero if a component is not used to provide a function, or a positive integer indicating the number of instances that a component is used to provide a given function. Thus, the existence of a component providing a certain function conveys design knowledge to the designer. This may be especially useful in identifying components that often lead to compliant solutions after effort flow analysis. In addition, the value of integer in each element of the function-component matrix may supply additional statistical information about the relationship between the component and the functions it provides.

A potential application of the component-function matrix is based on the design repository alluded to earlier. Using the component-function matrix as a design repository, a computational concept generator may be developed. The concept for a method is proposed that uses the known functional model for a product undergoing either initial design or redesign as input to the concept generator. The output from the concept generator is a list of potential component solutions that are extracted from the component-function repository and synthesized into concept variants.

8.3.4 - Relationship between S-Curves and Re-design approaches

A final area that may benefit from concentrated attention in the future is the relationship between the product evolution S-Curve [102] and the type of analysis carried out in effort flow analysis. One of the first concerns is establishing the location of the product of interest and the locations of competitors on an S-Curve. By comparing these two locations, it is proposed that a set of guidelines can be developed to give suggestions for the company performing the analysis on how to best improve their competitiveness in the market. In effort flow analysis, an existing product is examined to determine which pieces of can be combined in order to direct the evolution of the product.

It is hypothesized that product designers have made most of the N-Link and some of the C-Link combinations using intuition and experience to evolve the product. Because of this, most products that have reached a high level of evolution, like the umbrella, will require a focus on R-link analysis in order to produce a change in the product. This leads to two basic lines of inquiry. 1) What is the effect on the product, the company, and the market when a change is made to an R-Link? 2) When is effort flow analysis beneficial for products that are not highly evolved, and how might that affect the approach taken in effort flow analysis of that product?

Addressing the first question, redesign through R-Links can lead to two possible outcomes. First, although the product is believed to have "peaked" in evolution, effort flow analysis may show that such products are not at the peak of evolution, and still have room for improvement in their S-Curve position. Second, effort flow analysis may create a jump in the S-Curve, in which case a completely new market is opened to the product

beginning the evolutionary process anew. Although jumps in the S-Curve are likely than incremental improvements, they have much higher potential to benefit the company.

Another question that arises is whether analysis of other links (i.e. N-Links and C-Links) for products near the peak of evolution is cost effective. As discussed in the effort flow analysis process, N-link changes are the easiest to see and the most likely to be successful, leading them to be the first changes made. Because of the high likelihood of success for N-Link combinations, if an N-link remains after multiple redesign efforts, it is likely that changes could not be made because of irreconcilable differences between the combined component and the customer needs. However, some N-Link and C-Link combinations may still exist and a method for determining the efficacy of implementing those opportunities is needed.

8.4 - CONCLUSION

The product evolution methodology presented in this dissertation represents a foundational work capable of supporting a long-term research effort. The areas of research opportunities just described are but a fraction of the possibilities. Referring back to Figure 8.1, the work done in this dissertation moves the state of design science along the axis of understanding toward an explanatory theory for product evolution using component combination.

Movement along the generalization axis is less pronounced. This dissertation produces stepwise improvement toward a generalized theory of product evolution through component combination. The primary area of improvement developed here lies in an improved understanding of the role that compliant mechanisms play in enabling product evolution.

Finally, it is sincerely hoped that this work be adopted by the design engineering community as a methodology that may be implemented by practitioners in the field, and found to be a useful foundation for those researchers who may take up the gauntlet and push the frontier of design science in this area.

Appendix A - Component Naming Convention

NOTE: All references in this appendix are to the reference section for this bibliography only.

A.2 - A DESIGN NAMING CONVENTION FOR MECHANICAL PARTS

A.3 - ABSTRACT

A standard naming convention for mechanical parts is presented in this paper. Our approach to formulating an exhaustive list of human-made mechanical transmission artifacts classifies components as functional forms, geometric shapes, simple machines, and natural forms. The proposed component basis provides a framework for development of computational design tools, two such application are presented in the form of a concept generator using a function representation and a product evolution methodology.

Key words: component basis, design languages, product decomposition, function-component matrix, concept generator.

A.4 - INTRODUCTION

In conceptual design or redesign, the process of abstracting a product is essential to representing a design artifact or its sub-artifacts. At a conceptual level, details of the various devices are less important than the ability to represent complex objects using relatively simple messages [1]. The naming of artifacts has evolved since the beginning of human communication. Names are abstractions of physical artifacts. The abstraction conveys from the sender to the receiver a full understanding about a physical device through a simple word or collection of words representing the name of the artifact. The more specific the name, the more well understood the artifact. In the realm of physical devices, the component level is the lowest level that is generally discussed. "A component is a mechanism, described in terms of variables and constraints that can interact with other components only through variables associated with explicitly specified terminals [2]."

Components represent the fundamental artifacts from which mechanical systems are constructed. There are many ways to classify the names given to the components used in the design and fabrication of mechanical systems. With an understanding of the origins of component names, it is proposed that a basis set of names can be compiled that will allow the enumeration of any mechanical device using <u>only</u> those names found in the basis. Collections of names are given different labels depending on their intended use. Examples include lexicon, nomenclature, taxonomy, ontology, and dictionary. Several of these are discussed in this paper with the ultimate goal of developing a lexicon for mechanical components that conveys design knowledge using a commonly understood and fundamental set of abstractions.

A.5 - MOTIVATION

Concept Generation: Many of our research efforts focus on making existing, manual conceptual and embodiment design activities computable. Ultimately, we seek a suite of computational design tools. At the center of the suite of design tools, we envision a concept generator able to synthesize concept variants from a functional description. If this goal can be achieved, then the concept variants will be described in terms of components. A design team will then be able to base concept selection on quantifiable measures, since preliminary mathematical models of component performance can be formulated.

Before this goal can be achieved, a standard set of component names is needed so designers can capture and record design knowledge of specific products. For each product, a functional model identifies product function and a bill of materials documents all components. Using the two results, components can be related to the function(s) they solve. As component-function knowledge is recorded for many products, a repository of design knowledge is formed. The design knowledge repository will provide the engine of a computational concept generator. With a functional model of the product to be designed (or redesigned) known, a list of component solutions may be extracted from the component-function repository and synthesized into concept variants.

Communication: Communication of design information gives rise to a number of issues. Often different methods are employed in categorizing components, and the use of natural language is ambiguous in its interpretation among different designers. These issues make design communication difficult among different sections of the same organization or even among individuals. Researchers have previously sought to standardize a function vocabulary and failure mode concepts [20, 21] but there has been little effort to construct a standardized component basis. Establishing uniformity and consistency in the representation of components will improve designer communication within and between organizations.

A.6 - BACKGROUND

A.6.2 - The Lexicon Of Chenhall

Museums are in the business of collecting, cataloging, and classifying the artifacts of humankind. In order to carry out this business in a repeatable manner, a system of classification is needed for those artifacts. One of the tools used toward this end is a lexicon. According to Chenhall [1], "The lexicon … is based on the assumption that every man-made object was originally created to fulfill some function or purpose and, further, that original function is the only common denominator that is present in all of the artifacts of man, however simple or complex." The known (or assumed) function of an object represents the highest level of organizing principle upon which human-made artifacts can be classified and named. A logical system for naming objects consists of a hierarchical ordering based on three fundamental levels of terminology: (1) a controlled list of major categories; (2) a controlled list of classification terms; and (3) an open ended list of object names. Each of these levels is based on the function of the object:

Major categories are a very limited set of easily remembered functional classes.

Classification terms are carefully defined subdivisions of the major categories.
Object names are the words used to identify individual artifacts.
This approach to the classification is similar to that used in the Linnaean system of classifying species in biology [4]. In the Linnaean system, the two classes are the genus class and the species name; these are equivalent to the classification and object name respectively in the system of Chenhall. The classifications are defined very clearly, while the object names are left open ended. This approach allows those interested in the lexicon to add to the collected knowledge contained therein. When used properly, a classification and an object name from Chenhall's lexicon results in a name that is unique in all of humankind's creations.

A.6.3 - Other Approaches

Active research in the artificial intelligence (AI) field of knowledge capture and representation is closely related to the work reported here. In knowledge capture and representation for mechanical design, taxonomy is replaced by ontology. In general, ontology is a philosophical theory about the nature of existence, but AI researchers have adapted the term to describe "a shared and common understanding of some domain that can be communicated between people and application systems" [5]. Neches *et al* [6] claim: "An ontology defines the basic terms and relations comprising the vocabulary of a topic area."
One difficulty in developing ontology for mechanical devices is the naming of a device based on a consistent classification scheme. For example, does a long slender two-force member describe a link, a beam, or a shaft? Stahovich, et al. [7] claim that the fundamental ontology for mechanical devices should be based on object behavior not structure. Paredis, et al. [8] suggest that a complete description of a component requires the addition of form to the classification, where form specifies a particular instantiation of a component, e.g., a part number for a motor. Both approaches imply that behavior is a key element in classifying mechanical components. Does this clear up the issue of the *long slender two force member*? The behavior of this component is describable using the mathematical representation of the states of a device [2]. Modeling using the state representation of the component leads to the input/output relationship. Input/output relationships taken at a more abstract level are, by definition, the function of a component, device, or system. "A function of a product is a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form [11]." In the case of the *long slender two force member,* the input/output relationship is to *transmit force*, where *transmit force* is a function taken from the set of basis functions of Stone, *et al* [9]. Hence, it is proposed that the *function* of a component is the fundamental ontology for mechanical devices.

A.6.4 - Observations

In this work, we find common ground between our goal for a basis set of component names in mechanical design and Chenhall's lexicon for classifying human-made artifacts. Because most components used in mechanical design are by definition human-made artifacts, they must be describable in the lexicon of Chenhall. One difficulty is that the lexicon does not include all possible artifact names, in fact "Artifacts originally created to

be a physical part of some other object have, in most cases, been excluded from the lexicon" [3].

The ontological approach of the AI community takes a similar approach to component classification by using function and form as fundamental elements in classification. The inclusion of function is a consistent theme in both the practical approach of Chenhall and the virtual approach of the AI community. The presence of function is important as a linkage between the theory of knowledge capture and representation and the theory of design. An understanding of function is integral to the design process [10, 11]; hence, a natural relationship between components and function must exist. This concept leads to the approach taken in this work.

A.7 - RESEARCH APPROACH: OUR LEXICAL SCHEMA

This work represents the results of a first attempt at a comprehensive set of names for the components used in the design of mechanical devices. The schema used to classify the component names of this work is limited to artifacts that are best classified as mechanical effort transmissions (our major category), those objects primarily concerned with the transmittance of forces and torques. The classifications within this major category are as follows:

Functional Forms
Geometric Shapes
Simple Machines / Mechanical Powers
Nature

Functional Forms: This class contains component names that are based on the function performed by the component. The following examples include the name of a function and an object name derived from that function. The function names derive from the functional basis of Hirtz, et al. [20]. The examples are: guide➔guide, stop➔stopper, fasten➔fastener, clamp➔c-clamp, lock➔lock and contain➔container.

Geometric Shapes: This class contains component names that are based on the fundamental geometry of the component. Examples include: cylinder, ball, disk, and ring.

Simple Machines: This class contains component names that are based on the fundamental relationship between the component and one of the "simple machines" or "mechanical powers," as follows:

<u>Simple Machines</u>: lever, wedge, screw, pulley, wheel and <u>axle, and inclined plane</u>.

The simple machines, first called the Mechanical Powers, are well known from elementary school. Pappus of Alexandria first defined the mechanical powers in the eighth of a set of eight books written in the first part of the 3rd century [29].

Nature: Certain components are named based on their similarity to naturally occurring artifacts. These include biological or anatomical structures such as the limbs and organs of animals or physical phenomenon such as fluids and magnets. Example names include: arm, heel, and magnet. These component names are intuitive and common, and do not readily map to the other naming bases. Hence, the names derived from natural artifacts are included as a distinct class of component names.

A.8 - RESULTS: A COMPONENT BASIS

In this section, the set of names compiled is proposed as a basis set of component names for mechanical effort transmitters. As a basis, this compilation represents a complete set of names capable of enumerating any mechanical effort transmitter device using only those names found in the basis. Using each of the naming sources listed above as a filter, four sets of components can be formulated, each containing the fundamental name of the component, its synonyms, and a brief definition of the component.

An example of one of the sorted tables of component names representing the nature domain is contained in Table A.1. The complete set of component names harvested from the literature and technical reference publications results in 115 terms. This component basis is shown in Table A.2. The methodology for gathering the component names is based on a search of various technical reference books [12, 17], design texts [11, 12], museum nomenclature [3], dictionaries [13, 14, 15], and general tinkering with products and devices. The definitions contained in the tables are a compilation of various sources. The wording is made as general as possible to allow the definition to apply to the primary name and the associated synonyms.

A.9 - APPLICATION

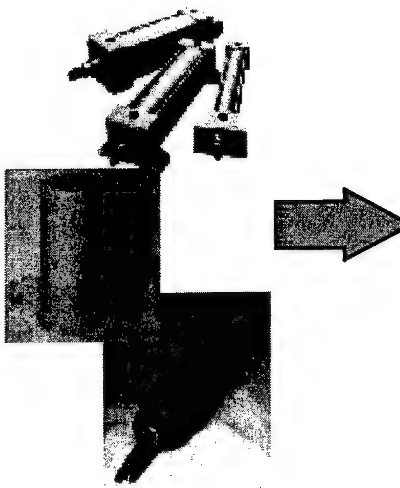
The establishment of a basis set of component names used in conjunction with the functional basis [9] facilitates the construction of a function-component matrix that is used as a preliminary version of a concept generation tool [18, 19]. The function-component matrix forms a relationship between components and their functions for a product where the product's components determine the columns of the matrix and the sub-functions, listed from the product's functional model, determine the number of rows. The matrix elements are filled with a zero if a component is not used to solve a given sub-function, or a positive integer indicating the number of instances that a component is used to solve a given sub-function. Thus, the existence of a component solving a certain function conveys design knowledge to the designer. The value of the function-component matrix element supplies additional statistical information about the component.

After multiple function-component matrices are developed, they can be aggregated into a single matrix. The aggregated matrix is called the *chi matrix* and can be represented by **X**. This approach is shown schematically in . The component basis is used to combine similar components into a single column of **X**. If more than one product has the same component, the matrix element χ_{ij} represents the cumulative number of times component j solves sub-function i.

In addition to simple frequency of occurrence, other information can be represented in **X**. Quantification of component quality or manufacturing or assembly ease is an example of other information that can be captured in the matrix.

Once design knowledge is captured in the **X** matrix, it can be reused to create new concept variants. This manipulation forms the foundation of the concept generator. The input to the concept generator is a functional model of the product to be designed. The functional model is expressed quantitatively in a filter matrix, **F**. The filter matrix is an nxn matrix with its rows and columns representing n sub-functions. Non-zero entries

appear on the diagonal corresponding to sub-functions of the new product's functional model. The filter matrix is shown schematically in Figure A.2.



component

function

	1	2	3	4	5	6	7
A		4		7	1		2
B	2	3		2		5	
C		2	6			3	4
D	4		2	4	6		6
E	6		3	6	3		3
F	3	5	3	3			
G		1			5	5	1
H	1	9		1	5	4	

Xmatrix

Figure A.1: A schematic Representation of the Function-Component Matrix.

To generate concept variants, the *nxn* filter matrix pre-multiplies the *nxm* **X** matrix (the function-component matrix) to produce a *nxm* morphological matrix of alternatives, **M**. This matrix manipulation is shown schematically in Figure A.2. Mathematically, the concept generator is formulated as:

$$\mathbf{F}\,\mathbf{X} = \mathbf{M}. \qquad (1)$$

The simplicity of the matrix manipulation understates the power of the concept generator. This one equation gives a mathematical way to compute a morphological matrix like those used by Pahl and Beitz [10], Ullman [25], Ulrich and Eppinger [24] or Otto and Wood [11]. Preliminary research on the concept generator has produced promising results for a future computational conceptual design tool [18].

As a more concrete example of the concept generator, consider the **X** matrix for an 18-product set. The components used to assemble the products, ranging from bathroom scales to a washing machine, are identified and named using the component basis of Table A.2. Once the individual function-component matrices are aggregated together, their corporate design knowledge can be used to generate new concept variants defined at a component level of detail. A portion of the 18-product **X** matrix that deals with the flow of solid is shown in Figure A.3 (note that only a subset of the observed components are shown). For instance, if a new product has the function "secure solid," then immediate solutions are found in the components of cover, bar, spring, pad, screw, nut and washer ring (lock).

Another application that is currently under investigation is the use of the product function matrix as a means to capture knowledge in the synthesis of compliant mechanisms. In this context, compliant mechanisms are components that provide a relative motion

function by virtue of their ability to deform. This application to compliant mechanisms is integral to a product evolution methodology known as effort flow analysis [26]. Compliant mechanisms present a particularly interesting challenge to component naming, as compliant mechanisms tend to be highly function-shared combinations of once separate components. In light of this function sharing, compliant features of components such as integral attachments and living hinges are called functional components to highlight the fact that the function provided was once solved by a separate component [26]. A short set of these functional components (compliant) is given in Table A.3. These applications represent the motivation for undertaking the establishment of a usable component basis.

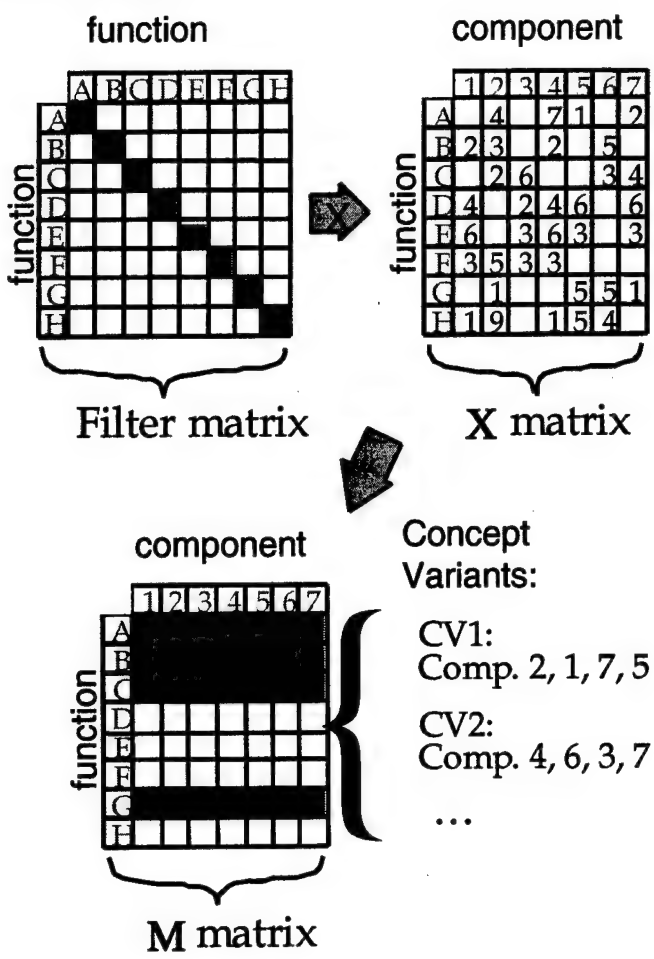


Figure A.2: A Schematic Representation of the Concept Generator.

A.10 - CONCLUSIONS AND NEXT STEPS

The component basis presented in this work represents an early, yet rigorous, attempt to identify a standardized set of mechanical components categorized as mechanical effort transmissions. The component basis uses the lexical scheme of Chenhall to identify major categories, to define classification terms and to list all mechanical components. Additionally, synonym(s), definition, and relative motion characteristics are given for each component. With the component basis, advanced concept generation techniques are possible that reuse existing design knowledge and improve design communication is.

Next steps include expanding the component basis to include other major categories of mechanical devices beyond the scope presented here. This expansion will allow further applications that include the use of the function-component matrix in the creation of a product repository as a tool in design synthesis [22, 23].

	cover	bar	tip	support	dial	guide	link	spring (linear comp.)	spring (linear tension)	spring (torsion)	spring (leaf)	gear	plate	needle	dial	lens	pad	grip	fastener	ring	screw	nut	washer ring	washer ring (lock)	bolt	collar
import solid	11	5	0	0	0	0	0	1	2	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
secure solid	9	8	0	0	0	0	0	1	3	0	1	0	0	0	0	0	4	0	0	0	4	2	0	1	0	0
couple solid	4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	3	1	0	0	0	0
source solid	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
position solid	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2
separate solid	2	1	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
store solid	2	4	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
control solid	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
guide solid	1	4	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
transport solid	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
stabilize solid	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
supply solid	1	2	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
change solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
stop solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
remove solid	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
regulate solid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
release solid	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
export solid	7	5	0	1	0	0	0	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure A.3: Partial X-matrix Aggregated Over 18 Products.

Table A.1: Mechanical Component Names Based on Nature (alphabetical)

Name	Synonyms	Definition
Arm	Limb, Appendage	Any structure resembling one of a pair of limbs peculiar to humans and other primates.
Bladder	Membrane, Sac,	Something resembling any of various sacs found in most animals and made of elastic membrane.
Blade	Cutting Edge, Knife, Razor, Compressor Blade, Turbine Blade, Rotor Blade, Fan Blade	An arm of a screw propeller, electric fan, or steam turbine. The broad flat or concave part of a machine that contacts the material to be moved or cut. Something resembling the blade of a leaf.
Body		The complete physical substance and structure of an organism, living or dead. A mass, especially one that is complete and independent.
Claw		A mechanical or other contrivance resembling the sharp horny nail with which the feet of birds and some beasts are armed. A curved device with sharpened extremity used for grappling or tearing.
Collar	Band	A ring, circle, flange, or perforated disk, surrounding a rod, shaft, pipe, etc., for restraining lateral motion. A short piece of pipe serving as a connection between two pipes.
Elbow	Ell	An angle in a tube, etc. A short piece of pipe bent at an angle to join two long straight pieces.
Fin		A projecting flat plate or thin expansion that occurs on the side or edge of a large portion of a structure. A fixed or adjustable airfoil or vane attached vertically to a flight vehicle to increase directional stability.
Finger		A short and narrow piece of any material.
Fluid	Liquid, Solution	Having the property of flowing, consisting of particles that move freely among themselves, to give way before the slightest pressure.
Gas	Ether	One of the three fundamental forms of matter, along with liquids and solids. Unlike a solid (and like a liquid), a gas has no fixed shape and conforms to the space available. Unlike a liquid, a gas has no fixed volume and conforms to the space available. When compared with solids and liquids, gases have widely separated molecules, have low density, and are easily compressed.
Heel	Heel block	Any part that resembles a shoe heel in shape, use, or location in relation to other parts
Jaw	Mouth	A device resembling in function the structure of the bony joint forming the mouth structure in an animal. The two halves of a vise between which a workpiece is clamped.
Leaf	Sheet, Page	A thin sheet or layer of other material produced either by beating out or by splitting. One of the metal strips of a leaf spring. A hinged part or one of a series of parts connected at one side or end by a hinge; a flap.

Lens		A piece of glass, or other transparent substance, with two curved surfaces, or one plane and one curved surface, serving to cause regular convergence or divergence of the rays of light passing through it.
Magnet	Lodestone, Electromagnet	A piece of lodestone, or a piece of iron or steel to which the characteristic properties of lodestone have been imparted, either permanently or temporarily, by contact with another magnet, by induction, or by means of an electric current.
Membrane	Casing, Covering, Crust, Film, Membranous Structure.	A thin pliable sheet-like tissue (usually fibrous), serving to connect other structures or to line a part or organ.
Nut	Wing Nut, Lug Nut, Female Screw	A perforated block having an internal screw thread, used on a bolt or screw for tightening or holding something.
Rib	Beam, Strut, Spoke, Spine, Spar, Ridge	A raised band or flange, especially one made upon a metal plate in order to stiffen it.
Tooth	Cog	A projection resembling or suggesting the tooth of an animal in shape, arrangement, or action. Any of the regular projections on the circumference or sometimes the face of a wheel that engage with
Wing	Airfoil	Each of the limbs or structures by which an animal or manmade craft is able to fly.

Table A.2: Basis Set of Mechanical Component Names (alphabetical)

Name	Synonyms	Domain	Definition
1. Actuator		Function	Any device that is moved a predetermined distance to operate or control another mechanical device.
2. Agitator	Mover, Stirrer	Function	A mechanical device used to maintain fluidity and plasticity, and to prevent segregation of liquids and solids in liquids, such as concrete and mortar.
3. Arm	Limb, Appendag e	Nature	Any structure resembling one of a pair of limbs peculiar to humans and other primates.
4. Axle	Stub Axle, Beam Axle, Axle Shaft	Simple Mach.	A supporting member designed to carry a wheel that may be attached to it, driven by it, or freely mounted on it.
5. Ball	Sphere, Orb, Globe	Geometry	A round or rounded body or mass.
6. Band	Belt, Strap, Girdle, Band, Restraint,	Geometry	An often-endless flexible band made of leather, plastic, fabric, or the like and used to convey materials or to transmit rotary motion between shafts by running over pulleys with special grooves. A narrow usually flat strip of a flexible material used for

	Strip, Leash, Tie, Lash		securing, holding together, or wrapping
7. Bar	Rod, Pole, Staff, Shaft, Rail, Stick, Dowel, Banister	Geometry	Long piece of rigid material that is slender in proportion to its length.
8. Beam	Girder, Rafter, Joist, Plank	Geometry	A large piece of squared material, long in proportion to its breadth and thickness, used to form important parts of a structure.
9. Bearing	Journal Bearing, Thrust Bearing	Function	Any part of a machine or device that supports or carries another part that is in motion in or upon it, such as a journal bearing or thrust bearing.
10. Bladder	Membrane, Sac,	Nature	Something resembling any of various sacs found in most animals and made of elastic membrane.
11. Blade	Cutting Edge, Knife, Razor, Compressor Blade, Turbine Blade, Rotor Blade, Fan Blade	Nature	An arm of a screw propeller, electric fan, or steam turbine. The broad flat or concave part of a machine that contacts the material to be moved or cut. (MW, 2001) Something resembling the blade of a leaf.
12. Block		Geometry	A compact piece of solid material.
13. Body		Nature	A mass, especially one that is complete and independent.
14. Bulb		Geometry	A rounded dilatation of any cylindrical structure.
15. Burner		Function	The part of a fuel-burning device, such as a furnace, boiler, or jet engine in which the fuel and air are mixed and combustion occurs.
16. Button	Push Button, Switch, Knob	Geometry	Any small rounded body. A knob, globule, disc, etc used as an interface to cause the activation of a device or component especially by closing an electric circuit.
17. Cam	Eccentric, Cam Plate, Camshaft	Simple Mach.	An eccentric curved wheel on a shaft used to transform rotary motion into reciprocating motion.
18. Carousel		Simple Mach.	A circular conveyor on which objects are kept in continuous motion.
19. Chip	Flake, Chunk, Integrated Circuit,	Geometry	A small, and especially thin, piece of material, separated by hewing, cutting, or breaking; a thin fragment chopped or broken off. A small wafer of semiconductor material that forms the base

	Transistor		for an integrated circuit.
20. Choke	Throttle, nozzle	Function	A restriction in a pipe to reduce fluid flow.
21. Chute	Runner, trough, slide	Geometry	A sloping trough with a flat bottom end; used to transport goods from a high level to a lower level.
22. Claw	Talon	Nature	A mechanical or other contrivance resembling the sharp horny nail with which the feet of birds and some beasts are armed, generally curved with sharpened extremity used for grappling or tearing.
23. Coil	Loop, spiral, helix	Geometry	A series of concentric circles or rings in which a pliant body has been disposed. Such a disposition or form in a body which is rigid.
24. Collar	Band	Nature	A ring, circle, flange, or perforated disk, surrounding a rod, shaft, pipe, etc., for restraining lateral motion. A short piece of pipe serving as a connection between two pipes.
25. Comb	Rake	Function	A combing tool with curved or straight tines, used for gathering dispersed material.
26. Condenser		Function	Any device or system that condenses.
27. Cone	Funnel	Geometry	A solid figure or body, of which the base is a circle, and the summit a point, and every point in the intervening surface is in a straight line between the vertex and the circumference of the base.
28. Counterweight	Ballast, Counterbalance	Function	A nonworking weight or load that is attached to one end or side of a machine in order to balance the weight carried on the opposite end or side. A working part that is attached and positioned at least partly in order to improve the balance of a machine.
29. Coupling	Union, Compression Coupling, Clamping Coupling	Function	A fitting, usually having inside threads only, used to connect two pieces of pipe or hose. A device used to connect coaxial shafts for power transmission from one to the other. A device designed for the purpose of mechanically coupling two or more objects.
30. Cover	Covering, Cap, Top, Lid, Hood, Shield, Shroud, Guard	Function	That which covers, anything that overspreads an object, with the effect of hiding, defending, sheltering, capping or enclosing it.
31. Cylinder	Container, Tube, Drum, Roll, Canister, Barrel, Cask,	Geometry	Any of various practical devices having the shape of a cylinder, such as the chambers of a revolver that hold the cartridges, or a container in which compressed gas is stored for use in pressurized operations. Any of a variety of devices having the cylindrical shape of a drum. A short cylinder revolving on an axis, used to turn other smaller wheels connected to it.

	Spool, Bobbin, Tank		Any cylindrical part of a machine. A horizontal cylinder or cone (or combination of the two) around which a rope or wire is wound in a hoisting mechanism.
32. Damper	Restraint, Brake, Vibration Suppressor, Dashpot	Function	A device used for reducing the amount of vibration in a mechanical system by increasing the amount of damping present in the system.
33. Disk	Diskette, Hard Disk, Floppy Disk, Compact Disk, Rotor	Geometry	Thin flat circular member.
34. Divider	Diaphragm, Partition, Panel, Wall, Barrier, Lining, Bladder	Function	Something that divides between separate spaces within a larger area
35. Door	Gate, Flap, Access Panel, Entrance	Function	A movable barrier, usually turning on hinges or sliding in a groove, and serving to close or open a passage into a space.
36. Elbow	Ell, Fitting	Nature	An angle in a tube, pipe, etc.
37. Enclosure	Container, Box, Shell, Holder, Casing, Crate, Crust, Chest, Skin, Armor, Housing, Skin, Sheath, Envelope, Wrapping, Cage, Case	Function	A thing fitted to contain or enclose something else.
38. Evaporator		Function	Any device in which evaporation occurs, especially one designed to concentrate a solution.
39. Extension		Function	A device allowing the movement by which the two elements of any jointed apparatus are drawn away from each other.
40. Fan	Windmill,	Geometry	Composed of radiating blades around a revolving hub.

	Impeller, Propeller		
41.Fastener	Fitting, Rivet, Nail, Lock, Clip, Catch, Snap Fit, Catch, Stud, Snap, Clasp, Saddle, Trap, Staple, Straight Pin, Press-Stud, Pop-Rivet	Function	A component used to make an object fast and secure, especially by pinning, tying, or nailing. (Excludes screws and their derivatives)
42.Fiber	Thread, Filament, Strand, String, Cord	Geometry	A tenuous thread-like body.
43.Filter	Strainer, Colander, Sifter, Trap Sluice, Sieve, Screen, Clarifier, Separator, Muffler, Silencer	Function	An apparatus used to prevent the passage of undesirable constituents in a flow based on different properties, e.g. specific gravity, phase, electric potential, size, frequency, etc.
44.Fin	Blade, Vane, Airfoil, Rudder, Slat	Nature	Something resembling, in shape or function, the membranous appendage extending from the body of a fish used to propel or guide the body. A projecting flat plate or thin expansion that occurs on the side or edge of a structure.
45.Finger	Tine	Nature	Something that resembles any of the five terminating members of the hand. A projecting piece (as a pawl for a ratchet) brought into contact with an object to affect its motion.
46.Fluid	Liquid, Solution	Nature	Having the property of flowing, consisting of particles that move freely among themselves, to give way before the slightest pressure.
47.Flywheel	Inertia Wheel,	Simple Mach.	A circular device that can store angular momentum.

	Momentum Wheel		
48. Fork	Split, Junction, Yoke	Geometry	A pronged instrument.
49. Frame	Skeleton, Structure, Support, Spine, Backbone, Undercarriage, Caliper	Function	A structure which serves as an underlying support or skeleton, or of which the parts form an outline or skeleton not filled in.
50. Friction Enhancer		Function	Facing material attached to a device that is used to reduce heat and increase friction.
51. Gas		Nature	One of the three fundamental forms of matter, along with liquids and solids. Unlike a solid (and like a liquid), a gas has no fixed shape and conforms to the space available. Unlike a liquid, a gas has no fixed volume and conforms to the space available. When compared with solids and liquids, gases have widely separated molecules, have low density, and are easily compressed.
52. Gear	Cog Wheel, Rack, Pinion, Ring, Sun, Planet, Worm	Simple Mach.	Wheels working one upon another, by means of teeth, or otherwise, in order to transmit force and motion between rotating shafts.
53. Grip	Handle, Hand Hold, Gripper, Manipulator, Graber	Function	A part allowing any action that is thought of as comparable to grasping something or keeping it in place. Something that grips or grasps.
54. Guide	Guide Pin, Guide Rod, Guide Bar, V-Guide, Channel, Pilot, Track, Path, Way, Locating Hole, Pathway, Trace, Rail, Jig Pin	Function	Any device, such as a track, bracket or pilot, by which another object is led in its proper course.

55. Hammer	Mallet, Impactor, Striker	Function	A hand tool, generally consisting of a solid metal head set transversely on a wooden handle; used for pounding nails, beating metals, and similar impact-related tasks. Any of various tools or machine parts that function in a manner similar to that of a hammer.
56. Heat Exchanger	Intercooler, Platen, Radiator	Function	A device used for the transference of heat from one medium to another
57. Heel	Heel block	Nature	Any part that resembles a shoe heel in shape, use, or location in relation to other parts
58. Hinge	Pivot, Axis	Function	The movable joint or mechanism that provides for the turning in a portion of a revolution of a lid, valve, gate or door, etc., or of two movable parts upon each other.
59. Hook	Catch	Geometry	A length of material, bent back, or fashioned with a sharp angle, often forming a part of something, as a pole, chain, etc., adapted for catching hold, dragging, sustaining suspended objects, or the like.
60. Inclined plane	Ramp	Simple Mach.	A surface sloped at an angle to the horizontal (or some other reference surface), which provides a mechanical advantage for raising loads.
61. Indicator	Knob, Handle, Dial, Face, Disk, Gauge	Function	An external plate or face on which revolutions, pressure, etc. are indicated by an index-finger or otherwise, as in a gas-meter, telegraphic instrument, steam or water-gauge, etc.
62. Inductor	Coil, Transformer	Function	A conductor or device in which an E.M.F. or current is induced.
63. Insert	Grommet Eyelet, Bushing	Function	An object of one material around which another material sets, solidifies, is formed, or which is forced into it after it has set. A removable, soft-material lining (often metal) used to limit the size of an opening. A firm material used to strengthen or protect an opening or to insulate or protect something passed through it.
64. Insulator	Lagging, Wadding, Padding, Filling, Insulation	Function	The material that provides the condition of being isolated by non-conductors to prevent the passage of electricity, heat, or sound.
65. Jacket	Water jacket	Function	A covering that encloses an intermediate space often used to allow a temperature-controlling fluid to circulate
66. Jaw	Mouth	Nature	A device resembling in function the structure of the bony joint forming the mouth structure in an animal.
67. Key	Half-Moon Key, Cotter Key, Shear Key	Function	A piece of material which is inserted between other pieces; usually, a pin, bolt or wedge fitting into a hole or space so as to lock the various parts together.

68. Leaf	Sheet, Page, Flap	Nature	A thin sheet or layer of material produced either by beating out or by splitting. A hinged part or one of a series of parts connected at one side or end by a hinge.
69. Lens		Nature	A piece of glass, or other transparent substance, with two curved surfaces, or one plane and one curved surface, serving to cause regular convergence or divergence of the rays of light passing through it.
70. Lever	Handle, Knob, Switch, Bar, Peddle, Rocker Arm, Lever Arm	Simple Mach.	A rigid structure of any shape (a straight bar being the normal form), fixed at one point called the fulcrum, and acted on at two other points by two forces, each tending to cause it to rotate in opposite directions round the fulcrum.
71. Lining	Inside Layer, Coating, Facing, Liner	Function	Any material occurring or placed next beneath the outside one. A covering or coating for an inside surface Material that lines or that is used to line especially the inner surface of something
72. Link	Connection, Pawl, Rod, Strut, Brace, Cross Piece, Girder	Function	Any connecting part transmitting motive power from one part of a machine to another. A member designed to resist pressure or thrust in a framework.
73. Louver	Shutter, Register, Vent	Function	An opening provided with one or more slanted fixed or movable fins for controlling a flow of air or the radiation of light.
74. Magnet	Lodestone, Electromagnet	Nature	A piece of lodestone, or a piece of iron or steel to which the characteristic properties of lodestone have been imparted, either permanently or temporarily, by contact with another magnet, by induction, or by means of an electric current.
75. Manifold	Rail, Tee, Fitting	Geometry	A high-pressure fitting with multiple ports all at the same potential.
76. Membrane	Casing, Covering, Crust, Film, Lining	Nature	A thin pliable sheet-like tissue (usually fibrous), serving to connect other structures or to line a part or organ.
77. Mesh	Net, Web, Grille, Screen	Geometry	An interwoven or interlocked structure. A device through which soft materials may be forced for reduction to finer particles.
78. Needle	Spine, Pointer, Indicator, Stylus	Geometry	A slender, usually pointed, indicator on a dial or other measuring instrument. Any of various slender hollow devices used to introduce matter (as air) into or remove it from an object.

79.Nozzle	Jet, Injector, Fuel Injector	Simple Mach.	A nozzle orifice that creates a continuous stream of concentrated and well-defined incompressible or compressible fluid. A device for converting fluid pressure into fluid velocity usually with minimum loss.
80.Nut	Wing Nut, Lug Nut, Female Screw	Nature	A perforated block having an internal screw thread, used on a bolt or screw for tightening or holding something.
81.Pad	Filling, Cushion, Wadding	Function	Something soft, of the nature of a cushion, serving to protect from or diminish jarring, friction, or pressure, or to fill up hollows and to fill out or expand the outlines of the body.
82.Pin	Hold Down, Jam, Post, Hinge, Axis, Pivot, Peg, Dowel	Geometry	A cylindrical piece used to fasten two parts together or to support one part that is suspended from another, allowing a degree-of-freedom. A short shaft that forms the center and fulcrum on which something balances, oscillates, or turns.
83.Piston	Ram, Plunger	Function	The working part of a pump, hydraulic cylinder, or engine that moves back and forth in the cylinder to control the passage of fluid.
84.Plate	Cover, Shield, Platen	Geometry	A smooth flat piece of material that is thin compared to its length and width.
85.Plug	Stopper, cap, bung,	Function	A piece of solid or firm material, driven into or used to stop up a hole or aperture which it tightly fits, to fill a gap, or act as a wedge.
86.Pulley	Step Pulley	Simple Mach.	A wheel or drum fixed on a shaft and turned by a belt or the like for the application or transmission of power.
87.Quadrant		Geometry	A thing having the form of a quarter-circle. An instrument that changes horizontal reciprocating motion to vertical up-and-down motion.
88.Receptacle	Container, Receiver, Vessel, Holder, Port, Outlet, Tray, Dish, Repository, Socket, Cup	Function	That which receives and holds a thing. Something into which another thing may be put. A hollow part or piece, usually of a cylindrical form, constructed to receive some part or thing fitting into it.
89.Release	Catch, pawl, lock	Function	A device that is designed to hold or free a mechanism as required.
90.Rib	Beam, Strut, Spoke,	Nature	A raised band or flange, especially one made upon a metal plate in order to stiffen it or facilitate attachment. Something resembling, in shape or function, one of the paired

	Spine, Spar, Ridge, Flange		curved bony or partly cartilaginous rods that stiffen the walls of the body of most vertebrates. For example, a traverse member of the frame of a ship that runs from keel to deck, a light fore-and-aft member in an airplane's wing, or one of the stiff strips supporting an umbrella's fabric.
91. Ring	Loop, Hoop, Disk, Washer, Band, Rim, Wheel, Hoop, Flange, Link, Race	Geometry	A circle of material, of any dimension, employed as a means of attachment, suspension, compression, force transmission, etc.
92. Rotor	Disk, Wheel, Impeller, Hub, Spindle, Nave, Indexer, Index Head	Simple Mach.	Any circular object that undergoes rotational movement such as in an electrical machine, turbine, compressor, blower, wheel, or contactor.
93. Scoop	Ladle, Dipper, Skimmer, Shovel, Bucket, Scoop, Spoon, Cup	Function	A concave utensil for bailing out, ladling or liquids or removing soft material.
94. Scraper		Function	An instrument used for scraping.
95. Screw	Jackscrew, Power Screw, Drive Screw, Lead Screw, Bolt, Fastener, Set Screw, Machine Screw, Lag Bolt	Simple Mach.	The general name for that kind of mechanical appliance of which the operative portion is a helical groove or ridge (or two or more parallel helical grooves or ridges) cut on the exterior surface of a cylinder. A long slender fastener consisting of a head, shank and external threads.
96. Seal	Gasket, O-Ring	Function	Any means of preventing the passage of gas or liquid into or out of something, especially at a place where two surfaces meet.
97. Shaft	Pole, Bar,	Geometry	A commonly cylindrical bar used to support rotating pieces or

	Rod, Shank, Pipe, Output Shaft, Driveshaft, Input Shaft, Jack Shaft, Half Shaft		to transmit power or motion by rotation.
98. Skid	Sled, Shoe, Runner, Rail	Function	A component either under or within a machine used to facilitate sliding of components relative to one another.
99. Spring	Cantilever Spring, Coil Spring, Leaf Spring, Plate Spring, Torsion Spring	Function	An elastic contrivance or mechanical device, usually consisting of a strip or plate suitably shaped or adjusted, which, when compressed, bent, coiled, or otherwise forced out of its normal shape, possesses the property of returning to it.
100. Sprocket		Simple Mach.	A toothed wheel that engages a power chain.
101. Stamp	Die, Punch	Function	A device used to exert pressure on a material, as to compress, shape, or mark it.
102. Stator	Stator Plate	Function	The stationary part of a machine around which a rotor turns.
103. Stop	Bumper, Snubber, Travel Limiter	Function	A device that is automatically activated by a predetermined displacement to limit the operation of a system.
104. Support	Foundation, Buttress, Crutch, Leg, Seat, Slab, Scaffold, Brace, Bed, Stanchion, Reinforcement, Buttress, Base, Pillar, Column,	Function	Anything that holds up, or sustains the weight of a body. A prop, support; pier or abutment.

	Joist, Bracket, Sole Plate, Anchor, Pedestal, Stand, Foot, Base, Jig, Fixture, Table, Underpinning, Piling, Bench, Crutch, Platen, Saddle, Prop, Structure, Stay		
105. Tab	Projection, Stub, Tang, Flap, Strip	Geometry	A projection, flap, or short strip attached to an object to facilitate opening, handling, or identification. (Grolier)
106. Tip	Point, Head, Top, End, Apex, Point, Stylus	Geometry	An apex or extremity of an object, designed to be a contacting point, end, cap, or cutting edge.
107. Tire		Simple Mach.	A continuous ring of rubber or other material, usually filled with air, that encircles the rim of a wheel that serves to support weight, absorb shock, provide traction, and so on.
108. Toggle	Switch, Flip-Flop	Function	A bistable device.
109. Tooth	Cog	Nature	A projection resembling or suggesting the tooth of an animal in shape, arrangement, or action Any of the regular projections on the circumference or sometimes the face of a wheel that engage with corresponding projections on another wheel especially to transmit force.
110. Tube	Pipe, Cylinder, Hose, Duct, Pipe, Conduit, Channel, Duct, Nipple, Sleeve	Geometry	A hollow body, usually cylindrical, and long in proportion to its diameter, used to convey or contain a liquid or fluid, or for other purposes.
111. Valve	Regulator, Tap, Flap	Function	Any of numerous mechanical devices by which the flow of liquid, gas, or loose material in bulk may be started, stopped,

	Valve, Rotary Valve		or regulated by a movable part that opens, shuts, or partially obstructs one or more ports or passageways. The movable part of such a device
112. Wedge	Block, Sliver, Slice	Simple Mach.	A piece of hard material, thick at one end and tapering to a thin edge at the other.
113. Wheel	Rim, disk	Geometry	Any of various machines, devices, or the like characterized by a revolving circular frame or disk.
114. Wing	Airfoil	Nature	Each of the limbs or structures by which an animal or manmade craft is able to fly.
115. Wire	Cable, Lead, Chain	Geometry	Metal wrought into the form of a slender rod or thread by the operation of wire-drawing.

Table A.3: Functional components (compliant)

1. Compliant Q-Joint	Quadri-lateral Joint	Combined	A compliant mechanism joint formed by connecting the ends of the members of a 4-bar mechanism using short-length compliant joints (living hinges) [28].
2. Compliant Coupling		Combined	A coupling containing a resilient member such as a metal spring or rubber disk; used to connect two rigid shafts that cannot be aligned.
3. Compliant Hinge	Living Hinge,	Combined	A coupling containing a resilient member such as a metal spring or rubber disk; used to provide a DOF between connected components.
4. Integral Attachmen t	Snap Fit	Combined	A feature formed into a part that provides attachment between parts and establishes part location, alignment, and orientation [27].
5. Compliant Shaft	Flexible Shaft	Combined	Any shaft that is made of flexible material.

A.11 - REFERENCES

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Appendix B - Effort Flow Analysis Guidelines

Table B.1: Table of All Hypothesized Guidelines for Empirical Product Study

N-GROUPS	
Recommendation	Combine groups of components connected only by N-Links into a single rigid component.
Guideline steps	Identify groups of components connected by N-Links. Develop design concepts that combine the grouped components into a single component. Apply the MATERIAL SELECTION guideline to the combined component. Model the resulting design(s) in a new effort flow diagram taking care to correctly characterize and label the links between the resulting combined component and the remaining components in the product.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Tool-Case, Compliars, Ice Cream Scoop, Wire Strippers, Tool Holder, Bicycle Frame, Forceps, Staple Remover
References	[1, 3, 6, 7, 12, 46, 63]
Guideline Support	****

C-GROUPS	
Recommendation	Combine groups of components connected only by C-Links into a single compliant component.
Guideline steps	Identify groups of components connected by C-Links. C-Groups can be of three types, minimum energy storage, prescribed energy storage, or a mixture of the two. For the portion of the C-Group where the primary function provided is to store strain energy, go to the C-LINK WITH STRAIN ENERGY STORAGE guideline. Generate design variants by combining the candidate parts via parametric changes to the existing geometry of the components. Model the resulting design(s) in a new effort flow diagram taking care to correctly characterize and label the links between the resulting combined component and the remaining components in the product. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	If the variants that result from parametric changes are unsatisfactory, apply the DISTRIBUTION OF COMPLIANCE guideline to perform more in-depth synthesis.
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Clip Spring to Cylinder in the pens Serotta Colorado → Ibis Silk Ti Bicycle Frames Compliant Ice Cream Scoop → Zerol Scoop
References	[129]
Guideline Support	****

C-LINK WITH STRAIN ENERGY STORAGE	
Recommendation	Replace C-Links and components providing the "storage/supply energy" function with an integral compliant component that uses strain energy to satisfy the desired energy storage/supply function.
Guideline steps	Identify C-Link interfaces and associated components that store or supply energy as their primary function. Apply the DISTRIBUTION OF COMPLIANCE guideline to the synthesis and analysis of potential solutions. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Kitchen clip product where the spring is replaced by the bending beam in the one-piece product. Bicycle suspensions where the coil spring of the multi-link suspension is replaced by the leaf spring/chain stay Stainless Ice Cream Scoop → Zerol Scoop & Compliant Version
References	[129]
Guideline Support	***
1-DOF R-LINK	
Recommendation	Combine components connected by a 1-DOF joint using a compliant mechanism.
Guideline steps	Identify an R-Link interface where a single DOF is provided, typically a pin joint or revolute joint.
Branch steps	If the relative motion in the link is small (see criterion section of this guideline, then apply the R-LINK SMALL MOTION guideline. If the relative motion in the link is large, see the R-LINK LARGE MOTION guideline.
Conditional steps	
Criterion	Small relative motion is generally described to be an angle of rotation, ($\theta \leq 360°$), that results in elastic behavior in the material of the redesigned component. Motion that does not satisfy the requirements above is described as lager motion.
Supplemental material	Solution Examples: Toolcase Hinges, Kitchen Clip, Tool Holder, CD Case, Bicycle Frame
References	[29, 129]
Guideline Support	****

R-LINK SMALL MOTION	
Recommendation	Combine components connected by small motion R-Links to form a compliant mechanism.
Guideline steps	Identify the links and components in the original product where small relative motion occurs. Apply the DISTRIBUTION OF COMPLIANCE guideline to the candidate components.
Branch steps	When the deformation must be confined to a small region of the mechanism, apply the LOCALIZED COMPLIANCE guideline to the analysis and synthesis of potential compliant solutions. When the deformation must be distributed over a large region of the mechanism, apply the DISTRIBUTED COMPLIANCE guideline to the analysis and synthesis of potential compliant solutions.
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	Small deflections in components where multiple cycles of operation are required are determined by the endurance limit of the material at the point of maximum stress. The maximum stress depends on the length of the mechanism over which deformation occurs. For a given amount of endpoint deflection, the shorter the length, the larger the maximum stress will be.
Supplemental material	Solution Examples: Ice Cream Scoop, Wire Stripper, 4-Bar Bicycle Frame, Clothes Hanger, Compliars, Forceps, Staple Remover
References	[6, 129, 132]
Guideline Support	**

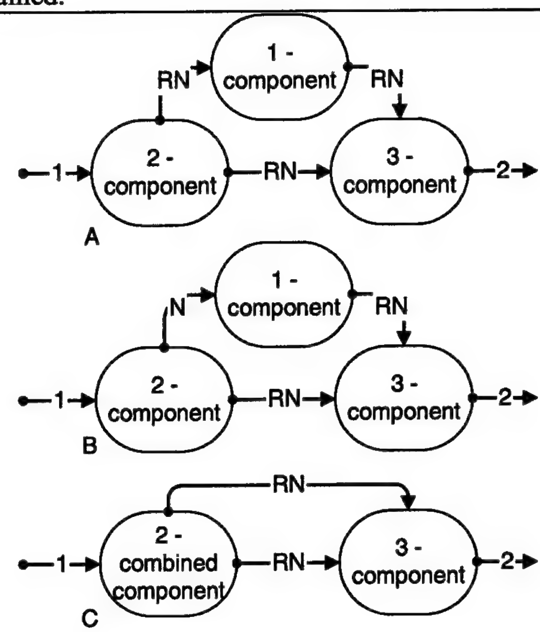
R-LINK LARGE MOTION	
Recommendation	Do not attempt to combine components connected by R-Links where the general relative motion is large and/or continuous except when all other options have been expended.
Guideline steps	In applications where a low number of cycles to failure are acceptable, a mechanism undergoing plastic deformation can provide large relative motion. If an application of this type can be identified, then apply the DISTRIBUTION OF COMPLIANCE guideline to the candidate components.
Branch steps	
Conditional steps	All other component combination or elimination opportunities should have been expended before going to a plastic deformation solution. Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	Small deflections in components where multiple cycles of operation are required are determined by the endurance limit of the material at the point of maximum stress. The maximum stress depends on the length of the mechanism over which deformation occurs. For a given amount of endpoint deflection, the shorter the length, the larger the maximum stress will be.
Supplemental material	Assembly hinges, "twist ties" or variants thereof, rivets, press in plastic fasteners
References	[132]
Guideline Support	* No product was observed to contradict this guideline, hence it is assumed to be valid.

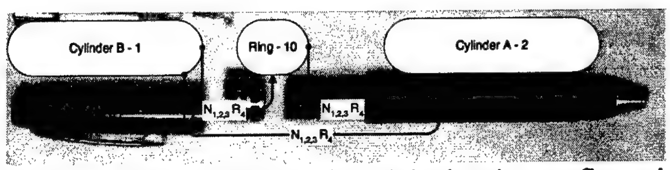
R-LINK → C-LINK	
Recommendation	Replace a R-Link connecting rigid bodies with a C-Link connecting compliant bodies.
Guideline steps	Identify a R-Link that provides small motion between components, but those components resist combination into a compliant mechanism. If all other component combination or elimination approaches have been attempted, consider making one or both of the rigid components connected by the R-Link into separate compliant components that are attached to one another. The compliant bodies will provide the DOF previously provided by the R-Link. Apply the DISTRIBUTION OF COMPLIANCE guideline to the candidate components.
Branch steps	Attachment methods include welding or adhesives.
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the compliant component(s).
Criterion	Small motion in components where multiple operation cycles are required is determined by the endurance limit of the material at the point of maximum stress. The maximum stress depends on the length of the mechanism over which deformation occurs. For a given amount of endpoint deflection, the shorter the length the larger the maximum stress.
Supplemental material	Bicycle Frames, Ice Cream Scoop, Bicycle Brake, Wire Strippers, Tool Case, Staple Remover
References	[130]
Guideline Support	**

REDUCE THE NUMBER OF DOF USED TO PROVIDE A FUNCTION	
Recommendation	Minimize the number of R-Links used to provide a given function or set of functions – move toward direct actuation between the effort source and the workpiece.
Guideline steps	Identify the R-Links associated with a relative motion function. Convert the R-Links to N-Links until the function is no longer provided. Insert the R-Link removed prior to functional failure. Apply the MATERIAL SELECTION guideline to the rigid body combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples Stainless Scoop to 4-Piece Scoop and ultimately to the 2-Piece Rigid Scoop
References	
Guideline Support	**

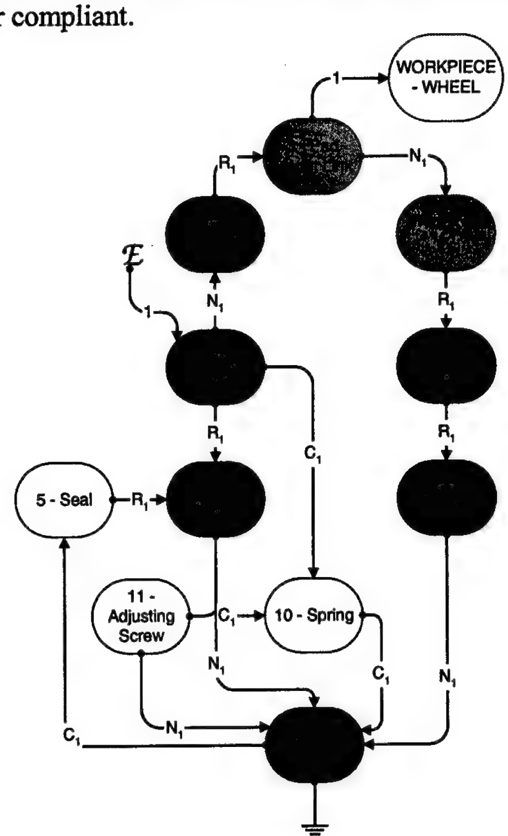
R-LINKS IN SERIES	
Recommendation	When R-links connecting multiple components have the same DOF (translation or rotation), then those components can be combined until an interface is reached where the required motions are for a different DOF.
Guideline steps	For R-Links in series where all the links are for 1-DOF revolute joints, combine the links into a single compliant mechanism that satisfies the path generation and end-point positioning requirements of the original device.
Branch steps	Apply the DISTRIBUTION OF COMPLIANCE guideline to the candidate components. Apply the MATERIAL SELECTION guideline to the combined component.
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component. If the NECESSARY CONDITIONS cannot be satisfied, remove one of the components from combination consideration and apply the NECESSARY CONDITIONS again. Repeat the removal of components process until the NECESSARY CONDITIONS can be satisfied, or the original configuration is returned. An Alternate approach is to apply the R→C-Link guideline to the series of components.
Criterion	
Supplemental material	Solution Examples: Tool Case, Swing Arm Bicycle Frame, Compliars, Forceps
References	[29, 130]
Guideline Support	*

PARALLEL R-LINKS	
Recommendation	Parallel R-Links may be combinable under certain scenarios.
Guideline steps	Determine if the parallel links are relevant using the REDUNDANT PARALLEL LINKS guideline Components connected by two parallel R or RN-Links; where one link provides a hinge behavior, and one link provides a intermittent constraint behavior (integral attachment, latch, etc.) can be combined at the hinge link to using the LOCALIZED COMPLIANCE guideline while maintaining the constraint behavior of the other R-Link using the integral attachment guideline.
Branch steps	
Conditional steps	
Criterion	
Supplemental material	Parallel links may represent networks of independent DOF, or they may represent redundant interfaces in initial models or models undergoing evolution. Nearly infinite permutations exist for parallel graph structures; for example, see An Atlas of Graphs [159]. Solution Examples: Kitchen Clip, Tool Case, Clothes Pin, Clothes Hanger, Ice Cream Scoop
References	[159]
Guideline Support	**

R-LINK NETWORK	
Recommendation	A serial R-Link graph structure that is in parallel with another R-Link may lead to contraction of the serial portion of the graph structure if the relative motion at the common nodes can be maintained.
Guideline steps	 Figure B.1: R-Link Network Structure Identify an R-Link network where serial RN or RC-Links are in parallel with another RN-Link (see Figure B.1(A)). Combination can only occur if the DOF between components 1 & 2 or between components 1 & 3 is the same as the DOF between components 2 & 3. Identify the RN-Link interface between components 1 & 2 or components 1 & 3 that has the same DOF any of the other two interfaces. Translate the R-Link behavior from the identified interface to the interface having the similar DOF, leaving the N-Link in place (see Figure B.1(B)). Combine the components now connected by the N-Link using the N-Group guideline (see Figure B.1(C)). The resulting parallel R-Links may now be evaluated for their applicability using the REDUNDANT PARALLEL LINKS guideline. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	

Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Pens, The rationale behind the statement about the DOF between the components in the network is based on the absence of interfaces with nodes outside the network of three node and associated R-Links. To accomplish this contraction in the SKILCRAFT pen (Figure B.2), choose one of the R-Links adjacent to the Ring, and move it to the other side of the Ring. This results in only N-Links on the path where the R-Link was removed, and N-Links can be combined if not prevented by material or assembly constraints. The resulting R-Link must now provide  the same number of DOF as the original series configuration. Figure B.2: R-Link Network in Skilcraft Pen
References	[99]
Guideline Support	**

1-DOF GROUNDED MECHANISMS	
Recommendation	A 1-DOF grounded mechanism may be designed as a compliant mechanism by making one or all of the links compliant.
Guideline steps	Identify a 1-DOF mechanism in the product of interest, and model the mechanism using an effort flow diagram. A 1-DOF grounded mechanism is identified by the presence of a ground link and a single kinematic DOF in the rigid body mechanism itself, the effort flow diagram of Figure B.3 is an example of a 4-bar grounded mechanism. If the mechanism provides an energy storage function using a C-Link, then combine any two adjacent members of the mechanism into a single distributed compliance mechanism to provide the energy storage function, and combine the remaining members using localized compliant mechanisms to provide the Allow DOF function. If the mechanism does not provide an energy storage function, then combine all the components using localized compliant mechanisms. Apply the MATERIAL SELECTION guideline to the combined components.
Branch steps	The Deltoid or Parallelogram Q-Joint may be used as one possible solution variant, e.g., Compliars, Forceps.
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component. If the fully compliant combination cannot satisfy the NECESSARY CONDITIONS, then remove the conflicting members from the compliant mechanism until the NECESSARY CONDITIONS can be satisfied.
Criterion	
Supplemental material	Solution Examples: 4-Bar Bicycle Frame, Bicycle Brake. Figure B.3 models a 4-Bar mechanism used in the original bicycle brake product. The spring stores energy relative to ground. Based on this guideline, the Ground Link and at least one of the connected members could be combined into a compliant member to produce the spring behavior. In the bicycle brake, a fully compliant mechanism is not achieved in the evolved product, due mainly to combined loading from braking forces. Hence, three possibilities remain: combine any three adjacent members into a compliant mechanism. The possibilities are; Arm-Pad Mount-Link; Link-Ground-Arm; or Pad Mount-Link-Ground. In either case, the attaching joints would be absorbed into the mechanism through the N-Links. Looking at the original mechanism, a relatively clear choice presents itself in the form of the Link. The Link is the most

	slender member of the original components, and thus lends itself most readily to conversion to a compliant member based on the I vs. BENDING STRESS guideline. The designer apparently chose to apply the Replace R-Links with C-Links approach rather than a full component combination of all three members, probably due to manufacturability. Additional rationale for the combination chosen comes from the direct functional conflict that arises when making the arm compliant. The arm must provide the Transmit Mechanical Energy function in the bending mode, which requires stiffness and conflicts with the need for compliance. Hence, the most logical choice is to select the option that makes the Link member compliant.  Figure B.3: 4-Bar Mechanism as Shown in Effort Flow Diagram
References	[29, 43, 130]
Guideline Support	**

<table>
<tr><th colspan="2">PARALLEL R & C LINK COMBINATION</th></tr>
<tr><td>Recommendation</td><td>Combine parallel R-Links and C-Links by incorporating the Allow DOF function of the R-Link with the Store Energy function of the C-Link into a single compliant mechanism.</td></tr>
<tr><td>Guideline steps</td><td>Identify parallel R & C Links in the graph structure; these may also be RN & CN Links.
Generate design concepts to combine the R-Linked components into a compliant mechanism.
Generate design concepts for the combination of the C-Grouped components that now includes the former R-Linked components.
Possible solutions to the C-Group combination can come from the C-LINK WITH STRAIN ENERGY STORAGE guideline.
An example is shown in Figure B.4 where a C-Group contains energy storage C-Links in <u>parallel</u> with R-Links.

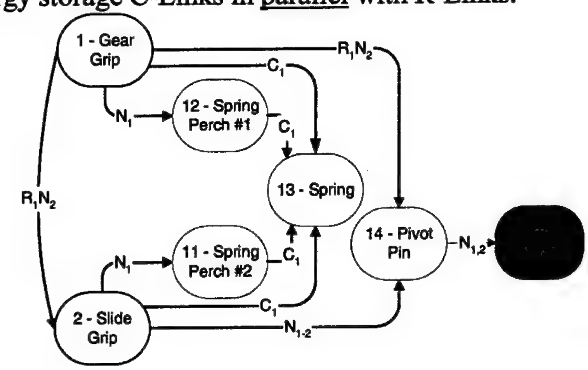


Figure B.4: Graph Structure for Parallel R & C Links

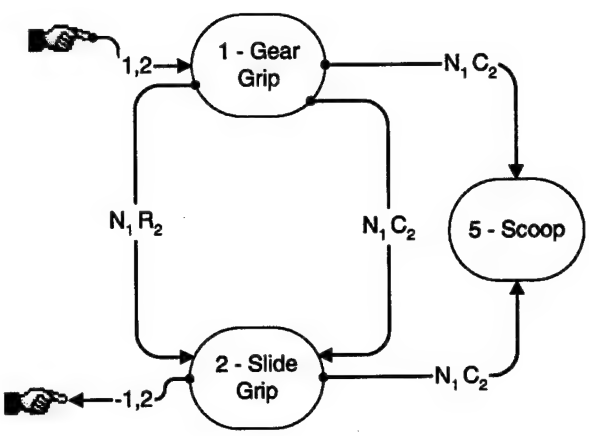
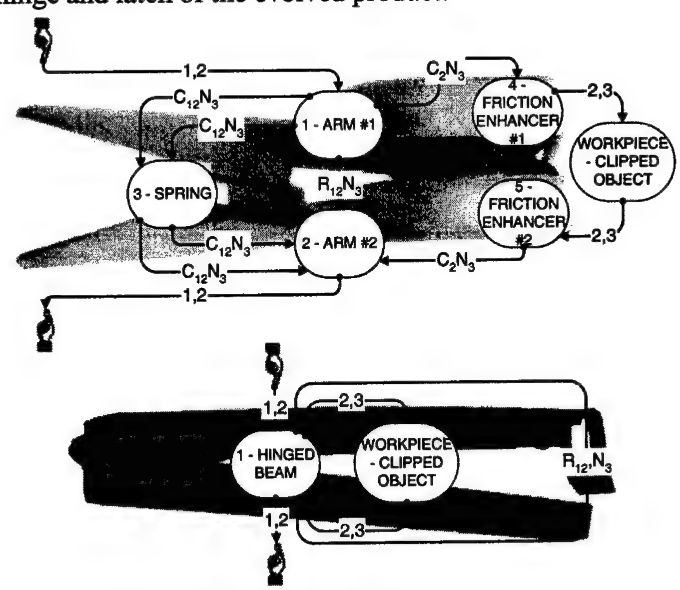


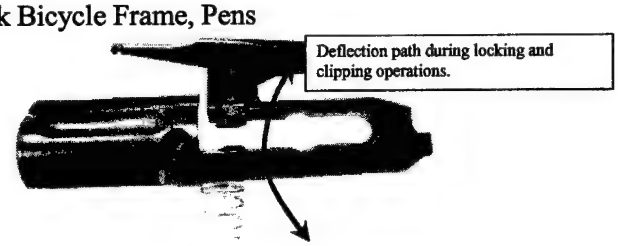
Figure B.5: Graph Structure for Evolved Parallel R & C Links. Note, one R-Link is maintained in this product due to functional</td></tr>
</table>

	constraints. Apply the MATERIAL SELECTION guideline to the rigid body combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	Parallel Structures are effort flow paths that originate at a single node and end at another single node without branching in between.
Supplemental material	Solution Examples: Kitchen Clip, Clothespin, and Ice Cream Scoop products
References	
Guideline Support	**
REDUNDANT PARALLEL LINKS	
Recommendation	Remove non-relevant parallel links from models undergoing component combination.
Guideline steps	Identify a parallel graph structure; the link type is immaterial. If the parallel links are the result of a previous graph contraction, then evaluate the links for their relevance to the combined component. Parallel links that are no longer relevant can be removed without loss of fidelity in the model. Parallel links that are found to be redundant (see Conditional steps) are removed from the diagram and evolution of the product proceeds using the appropriate guidelines.
Branch steps	If the parallel links are found to be relevant, or are in an initial model, then look to the PARALLEL LINKS guideline for component combination opportunities.
Conditional steps	Parallel links are redundant if the relative motion functionality can be satisfied with fewer links than are present in the current product.
Criterion	Nearly infinite permutations exist for parallel graph structures, for example, see An Atlas of Graphs [159].
Supplemental material	Solution Examples
References	[159]
Guideline Support	**

R & C ACTIVE FOR SAME OPERATION	
Recommendation	An R-Link can initiate C-Link behavior in a component. Take care to recognize interfaces where the R & C Link characterizations occur, as the complexity of combination through such an interface will be made more complex due the motion.
Guideline steps	Identify the interfaces where R & C Links occur. In a single operation diagram, an R-Link will be the characterization used for the interface. Pursue other component combination opportunities before attempting the coincident R & C Link interface. This approach may allow for a reduction of the complexity of the interfacial motion and allow the connected components to be more easily combined. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples
References	
Guideline Support	***
CR-LINKS	
Recommendation	When an interface consists of an R-Link and a C-Link, the two relative motions generally act in orthogonal directions; hence, combination is unlikely due to the more complex motion at the interface.
Guideline steps	Identify interfaces where RC-Links exist. Translate the R-Link behavior up or down the flow path from the identified interface to an adjacent interface having similar DOF, leaving the C-Link in place.
Branch steps	Treat the remaining C-Link using the appropriate guideline Treat the translated R-LINK using the appropriate guideline.
Conditional steps	The translation of an R-Link requires that an adjacent R-Link have the same DOF to allow successful translation. Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples
References	
Guideline Support	**

RN-LINKS – COMPLIANT COMBINATION	
Recommendation	RN-Links behave primarily as R-Links; therefore, give higher priority to the contribution of the R-Link in determining a combined solution. RN-Groups are combinable using the guidelines that treat various instances of the R-Link while continuing to provide the constraint behavior provided by the N-Link.
Guideline steps	Identify one or more RN-Links. Replace separate components connected by an RN-Link with a single compliant mechanism using the guideline that is appropriate for the R-Link configuration. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Pens, Ice Cream Scoops, Kitchen Clip, Wire Stripper, Tool Case, Tool Holder, Compliars, Forceps, Staple Remover
References	
Guideline Support	***

CN-LINKS – COMPLIANT COMBINATION	
Recommendation	CN-Links behave primarily as C-Links; therefore, give higher priority to the contribution of the C-Link in determining a combined solution. CN-Groups are combinable using the C-Group Guideline approach provided the required constraint on the DOF needed for the N-Link is achieved.
Guideline steps	Identify interfaces where one or more CN-Links occur. Treat the CN-Group as though made up of C-Links only. Combine the components connected by CN-Links by removing the link and joining the nodes into a compliant mechanism. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: Pens, Ice Cream Scoop, Kitchen Clip, Wire Stripper, Tool Case, Clothes Hanger, Clothes Pin, Compliars, Forceps, Staple Rem. This guideline is demonstrated by combination of the arms and spring, which produces the beams, hinge and latch in the evolved product of Figure B.6. The DOF constraint is changed from resisting a compressive load in the original hinge to resisting a tensile load in the evolved hinge. In addition, the on out-of-plane motion constraint at the interface between the arms of the original product is enforced by the hinge and latch of the evolved product.  Figure B.6: CN-Group Structure in Graph

References	
Guideline Support	***
TIME DEPENDENT BEHAVIOR IN COMPLIANT POLYMERS	
Recommendation	Avoid the use of polymer compliant mechanisms in applications where the mechanism is subject to sustained loads or deformations.
Guideline steps	Determine whether the combined component is to operate under sustained loading or sustained deformation. If either of the two previous conditions is true, visco-elastic behavior may result in the mechanism. Apply the MATERIAL SELECTION guideline to the combined component. If visco-elastic behavior is undesired, take one of the following mitigation approaches: a. reconfigure the design so the compliant polymer mechanism doesn't support sustained loads or deformations under normal operating conditions, or b. replace the polymer with a material not susceptible to visco elastic effects, or c. consider the addition of a non visco-elastic support mechanism.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples: 4-Link Bicycle Frame, Pens  Figure B.7: Augmented Compliant Polymer Mechanism For example, the compliant mechanism in the Clip Spring of the Pilot Explorer pen is augmented by a metallic coil spring (Figure B.7). The purpose of the spring is deduced to be creep prevention. The compliant polymer device performs all required operations when the spring is removed, but inclusion of a temporal aspect to the performance evaluation may lead to non-performance due to the effect of creep.
References	[29, 129, 136, 137]
Guideline Support	***

DISTRIBUTION OF COMPLIANCE	
Recommendation	Determine whether the embodied compliant mechanism should use a LOCALIZED or a DISTRIBUTED architecture for the compliant region.
Guideline steps	To facilitate ready replacement of the original component with the combined component, the architecture of the replacement component should maintain the same interfaces as the original component. The overall layout of the two mechanisms must be similar; therefore, the architecture of the original mechanism will provide an indication of the architecture for the evolved mechanism. Evaluate the geometry of the existing components to establish whether the motion generated in the existing mechanism is best provide by a Localized or Distributed compliant architecture. Deformation that is concentrated at a few regions of the mechanism is exemplified in cases such as those resulting from: -Pin Joint Replacement -Minimize Energy Storage Constraints, -Circular Path Requirements, and -Tensile Loading During Rotation. In the above cases, apply the LOCALIZED COMPLIANCE guideline to the analysis and synthesis of potential compliant solutions. Deformation that is distributed over a large region of the mechanism is exemplified in cases such as those resulting from: -Multi-link Mechanism Replacement, -Non-circular Path Requirements, -Energy Storage Requirements, -Bending Load Transmission Behaviors, and -Combined Loading Environments. In the above cases, apply the DISTRIBUTED COMPLIANCE guideline to the analysis and synthesis of potential compliant solutions.
Branch steps	
Conditional steps	
Criterion	Compliant joints are generally inappropriate in applications where the magnitude of rotation, $\boldsymbol{\theta \geq 360°}$. Large deformations occur during the operation of a combined component, if either the endurance limit or the yield strength of the material is exceeded at the point of maximum stress. The maximum stress depends in part on the length of the mechanism over which deformation occurs. For a given

	endpoint deflection, shorter lengths lead to larger maximum stresses. This large deformation criteria applies primarily for elastic deformations, but can be extended to plastic deformations by replacing the yield strength with the ultimate strength.
Supplemental material	
References	[29, 41, 105]
Guideline Support	****

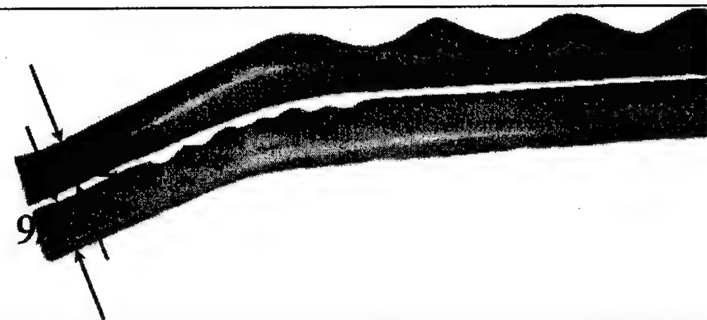
DISTRIBUTED COMPLIANCE	
Recommendation	Compliant solution architectures dictating that broad regions of a device be compliant are classified as distributed compliance problems.
Guideline steps	The analysis and synthesis of distributed compliant mechanisms where multiple components move in a relatively complex load and deflection environment is best carried out using continuum models for analysis. The analysis of distributed compliant mechanisms where fewer components move in relatively uncomplicated load and deflection environment is best carried out using the pseudo-rigid body model. CONTINUUM MODEL: The continuum model approach to the synthesis of distributed compliant architectures is typically a search using finite element modeling (FEM). The approach is to first define the boundary conditions for the compliant mechanism in terms of the locations, directions, and magnitudes of forces and deflections based on the envelope occupied by the components selected for combination in the original product. A fully populated mesh is defined to occupy the region of space available for the mechanism. The region is based on the envelope defined by the components in the original product. The loads or deflections expected or desired in the compliant mechanism are then imposed on the mesh. For applications where a minimum resistance to motion is required, the elements are manipulated so that strain energy is minimized for the overall mesh. For applications where energy storage is required, the elements are manipulated so that strain energy hits a target value for the overall mesh. PSEUDO-RIGID BODY: The pseudo-rigid body model approach treats the elements of the compliant mechanism as rigid members connected by pin joints. Each joint is modeled as a revolute joint and a spring, where the spring represents the strain energy of the compliant mechanism. Two possible considerations in the synthesis compliant mechanisms using bending beams in the pseudo-rigid body model are the relationships between the second moment of area and the bending stress, and between the length of the compliant member and the bending stress. See the criterion entries below for guidelines related to length and second moment of area.

	Once the topology of the mechanism is determined using either the continuum model or the pseudo-rigid body approach, apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	
Criterion	Apply the I vs. BENDING STRESS guideline. Apply the Length vs. BENDING STRESS guideline.
Supplemental material	Solution Examples
References	Continuum Model: [24, 36-41, 44, 45, 123-126] Pseudo-Rigid Body Model: [29-32, 34, 42, 43, 127-130] Bistable Mechanisms: [35, 131] Mechanical Advantage: [27]
Guideline Support	***

LOCALIZED COMPLIANCE	
Recommendation	Compliant solution architectures dictating that the small regions of the device be compliant are classified as Localized Compliance problems. Compliant mechanisms of this type are best analyzed using the pseudo rigid-body model.
Guideline steps	PSEUDO-RIGID BODY: The pseudo-rigid body model approach treats the elements of the compliant mechanism as rigid members connected by pin joints. Each joint is modeled as a revolute joint and a spring, where the spring represents the strain energy of the compliant mechanism. For mechanisms where the strain energy is to be minimized, the spring stiffness should be negligible in comparison to the other forces that act in the mechanism. Several rotation based mechanisms are possible to replace pin joints: Living Hinge, Assembly Hinge, Passive Joints (separate components maintained in contact by compressive forces), Q-Joints, Cross Axis Flexural Pivots, Torsional Hinges, and Split Tube Flexures. Each of these types of compliant joints is discussed in detail in the references given below. Once a joint replacement configuration has been chosen, apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	
Conditional steps	Compliant *living hinge* joints are inappropriate in applications where large compressive loads must sustained, as the compressive load causes the hinge section to buckle. Compliant *living hinge* joints are inappropriate in applications where the compliant joint must provide an energy storage function.
Criterion	Compliant joints are inappropriate in applications where the magnitude of rotation, $\boldsymbol{\theta \geq 360°}$.
Supplemental material	Solution Examples: CD Case, Tool Case, Kitchen Clip, Bottle Cap, Wire Strippers, Clothes Hanger, Clothes Pin, Forceps,
References	Living Hinge, [29, 127, 132, 133] Assembly Hinge, [132] Passive Joints, [29] Q-Joints, [28] Cross Axis Flexural Pivots, [134] Torsional Hinges, [29] Split Tube Flexures [135]
Guideline Support	**

INTEGRAL ATTACHMENT	
Recommendation	Use integral attachment mechanisms to replace traditional fasteners.
Guideline steps	Identify the links associated with fasteners. OPERATIONS End user operations represent intermittent fasteners such as latches as RN-Links. End user operations represent permanent fasteners such as screws and rivets as N-Links. Assembly operations represent fasteners as R-Links during installation of the fastener, or as N-Links after the fastener is installed. In either case, evaluate all instances of fasteners as opportunities for component combination using compliant integral attachment. A significant body of literature exists on the design and integration of Integral Attachment, see the listed references for more information. Apply the MATERIAL SELECTION guideline to the rigid body combined component.
Branch steps	
Conditional steps	Apply the NECESSARY CONDITIONS guideline to the combined component.
Criterion	
Supplemental material	Solution Examples
References	[132, 147-158]
Guideline Support	***

I vs. BENDING STRESS	
Recommendation	When a bending deflection is specified, reduce the second moment of area to reduce the stress and thus the likelihood of fatigue failure in a compliant mechanism.
Guideline steps	The mechanics behind this result follow the argument that a desired deflection is specified: $$\delta = \frac{FL^3}{3EI} \quad \text{(B.1)}$$ $$I = \frac{bh^3}{12} \quad \text{(B.2)}$$ The maximum or minimum force required to achieve that deflection is then specified, and equation A.x1 is solved for the force ***F*** as in equation A.x3. Equation A.x3 is then substituted into equation A.x4 for ***F*** resulting in a relationship for stress that is a function of ***h*** for a given deflection shown in equation A.x5. $$F = \frac{3\delta EI}{L^3} \quad \text{(B.3)}$$ $$\sigma = \frac{h}{2}\frac{FL}{I} \quad \text{(B.4)}$$ $$\sigma = \frac{3h}{2}\frac{\delta E}{L^2} \quad \text{(B.5)}$$ Note that as ***h*** is reduced, the stress is reduced, as is the second moment of area, ***I***, hence to achieve a given deflection with a minimum tensile stress due to bending, the object is to reduce ***I***. The most effectively way to do this is to reduce ***h***. This result is related to the guideline proposed by (Bergland, Magleby, & Howell, 2000) where it is stated "Avoid adding material to a compliant segment if it experiences static or fatigue failure in bending." This guideline is confirmed in the second iteration of the evolved ice cream scoop, where the thickness of the bending beam compliant segment is reduced; see Figure B.8 for details.

	 Figure B.8: Reduced Second Moment of Area in a Bending Beam
Branch steps	
Conditional steps	
Criterion	
Supplemental material	
References	[29, 129]
Guideline Support	***

LENGTH vs. BENDING STRESS	
Recommendation	When a bending deflection is specified, increase the length over which the deflection is distributed to reduce the maximum stress and thus the likelihood of fatigue failure in a compliant mechanism.
Guideline steps	The mechanics behind this result are based on a small deflection assumption, and follow the argument that for a specified desired deflection: $$\delta = \frac{FL^3}{3EI} \quad \text{(B.6)}$$ $$I = \frac{bh^3}{12} \quad \text{(B.7)}$$ The maximum or minimum force required to achieve that deflection is then specified, and equation A.x1 is solved for the force ***F*** as in equation A.x3. Equation A.x3 is then substituted into equation A.x4 for ***F*** resulting in a relationship for stress that is a function of $\boldsymbol{1/L^2}$ for a given deflection shown in equation A.x5. $$F = \frac{3\delta EI}{L^3} \quad \text{(B.8)}$$ $$\sigma = \frac{h}{2}\frac{FL}{I} \quad \text{(B.9)}$$ $$\sigma = \frac{3h}{2}\frac{\delta E}{L^2} \quad \text{(B.10)}$$ Note that as ***L*** is increased, the stress is reduced, hence to achieve a given deflection with a minimum tensile stress due to bending, the object is to increase the length over which the compliance is distributed.
Branch steps	
Conditional steps	
Criterion	
Supplemental material	
References	[29, 129]
Guideline Support	**

MATERIAL SELECTION	
Recommendation	Identify one of the existing materials from the components being combined as a first candidate for use in the combined component.
Guideline steps	Select compliant materials with the highest strength-to-modulus ratio to allow larger deflections before failure. This ratio is one of the most important factors in selecting a material for a compliant mechanism [29] If one of the existing components cannot satisfy the necessary conditions, then choose a suitable material using a material selector such as The Materials Selector by Ashby [105]. Ensure the material has an endurance limit sufficient to provide the desired design life. For polymers, an estimate of the endurance limit is given by: $\boldsymbol{0.2S_{ut} \leq S_{e'} \geq 0.4S_{ut}}$
Branch steps	
Conditional steps	
Criterion	
Supplemental material	
References	[29, 104, 105, 115, 136, 160, 161]
Guideline Support	****

NECESSARY CONDITIONS	
Recommendation	The necessary conditions for component combination must be satisfied for any proposed component combination opportunity.
Guideline steps	Component combinations must satisfy: The three necessary functional conditions: <u>Degree-of-Freedom Condition</u>: *The original degree-of-freedom based functions must be maintained in the resulting combined component, rigid or compliant.* <u>Energy Transmission Condition</u>: *The material of the combined component must satisfy the energy transmission functions required for the product.* <u>Actuation Force Condition</u>: *The actuation force of the resulting rigid or compliant mechanism must be within the reasonable and achievable bounds of the actuating component.* These three functional conditions represent necessary conditions for component combination, but they do not represent sufficiency requirements, as they do not capture the full spectrum of possible functional requirements. The three solid-mechanics based laws: *<u>Strain-Displacement Law</u>,* *<u>Stress-Strain Law</u> (Material Constitutive Relationship),* *<u>Equations of Equilibrium</u> (Force or Stress).* These three laws are inviolable in all cases, and completely define the state of the material in the product. They are intrinsic to the physics of mechanical efforts. The relationship between the physical laws and the functional conditions is best described as a system of coupled relationships. These three functional conditions map to the three solid mechanics laws to form a system of relationships that must be satisfied in every combined component.
Branch steps	
Conditional steps	
Criterion	
Supplemental material	
References	[1, 6, 24, 29, 47, 49, 50, 64, 68, 83, 104, 115, 130, 171, 172]
Guideline Support	****

FUNCTIONAL COMPONENTS	
Recommendation	Decompose multi-functional components into virtual links and nodes representing the individual interfaces and features of the component used to provide the functions of the original component.
Guideline steps	Identify a multi-functional component. Decompose the component into nodes representing the features of the original component where the individual functions are provided. These new nodes are called *functional components.* Locate the *functional component* nodes in the effort flow diagram following the topology of the original component and its relationship to the other components. Characterize the links between each of the *functional components* and all other components, treating the *functional component* as if it were a regular component of the product. Characterize the links that exist between each of the *functional components* themselves. Apply all guidelines that are appropriate for the arrangement of nodes in the new representation. Redesign the product based on the variants that result from the new model.
Branch steps	
Conditional steps	
Criterion	
Supplemental material	Components that serve more than one function can be separated into multiple, equivalent single-function components that can potentially afford combinations not previously feasible because of relaxation of material or other constraints for the single-function components.
References	[1, 83]
Guideline Support	**

CHOOSING BETWEEN CONTRACTION OPTIONS	
Recommendation	When a graph structure provides more than one choice for graph contraction, choose the contraction that leads to the fewest number of remaining inter-node links.
Guideline steps	Identify a group of components with multiple component combination permutations. Evaluate each possibility and choose to combine the components using the permutation that produces the fewest inter-nodal links. Apply the NECESSARY CONDITIONS guideline to the combined component. Apply the MATERIAL SELECTION guideline to the combined component.
Branch steps	An alternate approach is to pursue each permutation to its reasonable end and evaluate the resulting variants using the NECESSARY CONDITIONS guideline.
Conditional steps	If the combination cannot satisfy the NECESSARY CONDITIONS, then proceed with the variant having the next fewest inter-nodal links and re-apply the MATERIAL SELECTION and NECESSARY CONDITIONS guidelines.
Criterion	
Supplemental material	Solution Examples: Tool Hanger, Tool Case, Bicycle Brake For example, combine components across the N-Links and C-Links shown in Figure B.9 into a single "mega component" in variant #2 leaving the other components in their original state. Compare this choice to variant #1, which distributes the Spring and Hinge Pin combinations over the Base and Arm components respectively. Applying the "mega-component" approach results in a clearer picture of the connectivity between the nodes of the combined component and the remaining nodes. In addition, the combination of all the components into a single node implies that only one new component must be designed to mate with the remaining original interfaces that remain intact in the new design.

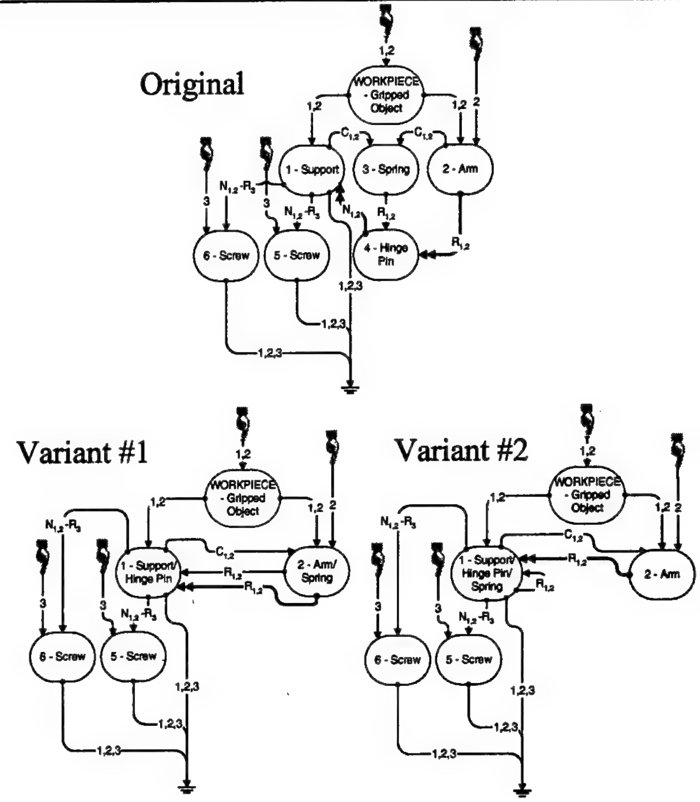


Figure B.9: Example of Choosing a Combination Opportunity

References	[8]
Guideline Support	**

Appendix C – Empirical Study Product Groups

Table C.1: Empirical Study Product Groups

Product Group	Product	Product Group	Product
Pens	Skilcraft	Kitchen Clip	Chip Clip
	Bic		Pampered Chef
	Papermate	Container Lids	Coffee Mate
	Orange Ad		One Piece
	Pilot	Wire Stripper	Pliers type
Ice Cream Scoop	Stainless IC Scoop		Compliant
	Plastic IC Scoop	Toolcase	Stack-On 19-Piece
	Zerol IC Scoop		Dewalt 10-Piece
	4-Piece Scoop		Skil 5-Piece
	2-Piece Compliant Scoop		Dewalt 4-Piece
	2-Piece Rigid Scoop		B & D 1-Piece
CD Case	Crystal Case		Metal 3-Piece
	3M Case		Metal 1-Piece
	Verbatim Trim-Pak ™	Bicycle Frames	Weyless
	Clam Shell Case		Serotta Road
Fish Hook Remover	Fish Hook Remover		Serotta Colorado
	Complier		Ibis Silk Ti from Serotta Colo.
Forceps	Locking Forceps		Theoretical 4-Link Susp.
	Blue		Cannondale

	Q-Joint Forceps		
Staple Remover	Office Depot	Bicycle Brakes	Shimano
	MADLab		Tektro
	Stanley/Bostich	Clothes Hangers	9-Piece
			5-Piece
			4-Piece
			3-Piece
			1-Piece

Appendix D - Prototyping Plan

Proposal of a Prototype Partitioning Strategy for the Umbrella Re-design Project
Prepared for Monty Greer

By Riyad Moe
November 15, 2001

D.1 - Overview

In order to enhance the success of the Umbrella Re-design Project, a prototype partitioning strategy was tailored to the specifics of this project using the method described in my research. The results of applying the strategy will be presented in a case study. This document presents the prescribed strategy.

First the prescribed strategy is described in general. Second, the specifics needed to apply it to this project are presented. Third, the documentation that is needed to support the case study is described. Fourth, the execution of the method for creating this particular partitioning strategy is detailed. Lastly, an explanation of the method for creating partitioning strategies is described.

D.2 - Prescribed Strategy – In General

The prescribed strategy can be summarized in 5 points:

- The umbrella re-design effort should be broken into two iterations. Each iteration should start with concepts of what will be prototyped. Each iteration should end with a design review in which the prototypes are evaluated against the project requirements.

- In each iteration, the design, fabrication, and testing of at least three different concepts should be attempted, concurrently.

- Midway through each iteration the initial designs concepts and project timeline should be reevaluated and adjusted based upon any new and relevant information.

- The design review at the end of the first iteration should evaluate the demonstration requirements (e.g. are the recommendations of the design evaluation process implemented, does the new componentry fit in place, can it be assembled, is there a locked closed position, is there a locked open position, is the device self-actuating in opening, etc.) Also, lessons learned related to design should be reported.

- The design review at the end of the second iteration should evaluate both demonstration requirements and functional requirements (e.g. what is the ultimate strength of the device, what is its closed volume, what is its weight, what is the manufacturing cost, etc.). Total project expenses should be reported. Also, a clear statement of design success or failure should be made.

D.3 - PRESCRIBED STRATEGY – IN DETAIL

The following information is based upon information provided by Mr. Greer

Start date January 18

End date March 30 (approximately)

Deliverables A physical device that performs the primary expected functions of an umbrella. A manufacturing cost estimate of the device. Test data that compares the device against a predicate device.

Budget No specific limit has been set on resources internal to UT. No budget has been approved for resources external to UT.

Development Team Mr. Greer and any resources he can mobilize.

Design Review Team Mr. Greer and Dr. Wood

Implementing the points of the general strategy to the specifics of this project results in the following proposed actions. These steps are shown schematically in Figure D.1.

On January 18th the project will start in earnest with the proposal of three design concepts, designated Designs A, B and C.

On February 1st these concepts and the project timeline will be reassessed. It will be determined if the proposed designs, proposed fabrication methods or proposed testing methods should be changed, or possibly abandoned and replaced with something better. The adjusted designs are designated Designs A', B' and C'. Also, it will be determined if the project timeline needs to be adjusted. It is requested that Dr. Wood, be advised of or contribute to these adjustments.

On or before February 22nd a review of test results of the three design will be held. At this review only the demonstration requirements need to be evaluated. Any functional results are beneficial, but not necessary. Also, at this time three more designs, designated Designs D, E and F, will be proposed for the second iteration.

On March 8th these concepts and the project timeline will be reassessed. The adjusted designs will be designated Designs D', E' and F'.

On or before March 30th a review of test results of the three design will be held. At this review the demonstration and functional requirements will be evaluated against requirements, expenditures and elapsed time will be reported, and the formal declaration of project success will be made.

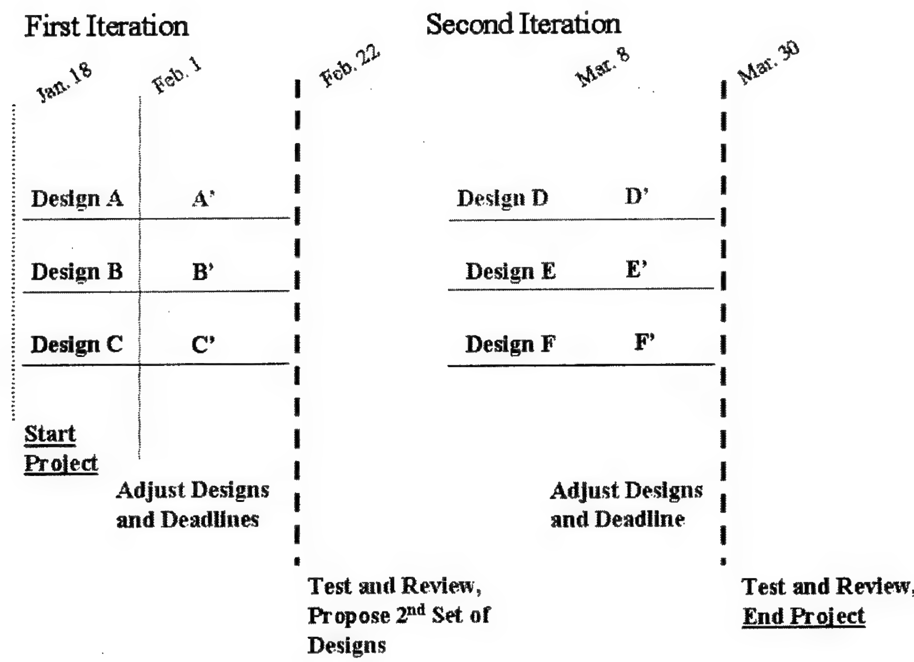


Figure D.1: Schematic Representation of Prescribed Partitioning Strategy

Appendix E – Compliant Mechanism Survey Responses

Ashok Midha

How do you go about identifying the products in which you will use compliance as a solution?

One potential category is when in the task prescription, force/torque-deflection or energy-deflection requirements are made. In other other words, energy management is called for which takes the form of requiring certain force-or torque-deflection behavior in actuation of the mechanism. Or, it may simply be a matter of potential energy storage with displacement, as in a handtool with a return spring.

Another motivator may be a desire to reduce the number of parts for ease of manufacturing and/or assembly. Energy storage may be another requirement. This would work well in this methodology. If energy is not a concern, and only kinematics is, then the concern would be to minimize the energy storage in carefully designing the compliant mechanism. The benefit could still be in the manufacturing and assembly aspects.

Some mechanisms may be injection molded. This limits the possible designs to strengths derived typically from the materials with which the part may be made. The significant benefits again are due to fewer pieces, and manufacturing and assembly aspects. If more complex compliant mechanisms are created using spring steel flexural segments, say, then clearly the benefits are limited to higher magnitudes and precision of force/torque/energy requirements, and some other properties, e.g. no clearances, lash or need for lubrication, etc.

An interesting example in selecting the use of compliant mechanism is as follows: Let's say a constant force device is required. One might be able to design an electromechanical system to accomplish this. Due to the normal compliance in even the "rigid" parts, active control would be necessary to insure constancy of force (not too convenient). A compliant passive mechanism may be designed so it is unmindful of any extraneous compliance in the system, and would maintain the constant force level at all times. Again, this might be categorized as a compliant mechanism problem requiring energy management.

Is your approach to this decision systematic, or intuitive?

I would say "intuitive;" no design methodology currently exists for making such decisions. There may be an opportunity to formalize the above thoughts and others.

What limitations do you see in the commercial use of compliant mechanisms?

Consumer education is needed to overcome the use of seemingly weaker materials and to reinforce the idea that multiple benefits may indeed be integrated into the compliant mechanism continuum. In some instances, it may be difficult to compete with the traditional devices due to the rigidity of the parts and their resulting strength.

What is your vision of the future of compliant mechanisms?

It is my firm belief that we've only but scratched the surface of this area. The applications for compliant mechanisms are limitless, in everyday use. It would appear that just about any current product could be designed better by integrating improvements rendered possible by use of compliant mechanism concepts, yielding the benefits I enumerated above. This may be hard to believe, but the philosophy would dictate this to be so. Only continued developments and applications would establish this to be the case in time.

Larry Howell

We could have a very long discussion on the questions you asked and it's hard to say too much by e-mail. A lot of my thoughts are in the book I just finished "Compliant Mechanisms" published by John Wiley & Sons (you can find it on Amazon).

There are some very simple rules of thumb that can be used. For example, if something has a combination of a linkage and springs, it is often a good candidate for replacement by a compliant mechanism.

Other factors are the need for high precision (because of the elimination of backlash in pin joints, etc.) and you will find many high precision instruments use compliant mechanisms. Planar fabrication is another issue - such as in micro-electromechanical systems (MEMS) or even in using stamping processes to make complex mechanical devices rather than just structures. There are other factors as well, but these are a few.

We have developed some approaches that try to systematically determine when compliance will be useful but it's mostly preliminary work (however, we did present a paper at the 2000 DETC on design rules for compliant mechanisms).

We currently have a grant for the commercialization of compliant mechanism research so we have been addressing some of these issues, including limitations. We have found that mass production of metal compliant mechanisms is a big problem, as is injection molding long thin flexible segments. For example, we

have a very nice overrunning clutch with centrifugal throw-out, but when a company said they would like to make 5000 per day and make them out of steel, we didn't know how to do it (we presented a paper at the 2001 DETC that began to address this problem). Pushing these boundaries on the abilities are what make research interesting. The current state of the art is such that many applications are possible that would not have been possible a short time ago, and more will be possible in the future. We are having success in licensing our compliant mechanisms patents to companies who are putting the products on the market.

The future of compliant mechanisms is exciting. We will see more commercial products come out that will provide competitive advantages to the companies that implement them. The research will continue in the modeling, analysis, design, and manufacturing of compliant mechanisms, and they will be used extensively at the micro and nano levels.

I hope this is helpful.

Larry

Suresh Ananthesuresh

How do you go about identifying the products in which you will use compliance as a solution?

In most products, some part of them can be replaced by compliant parts. I usually look for total-compliance (as in one-piece) solution. If the range of motion is not too much and it involves a spring of some sort, that is a candidate for a one-piece compliant design. Single actuation is another requirement, but not always (for example, when two actuators serve two different decoupled functions).

Is your approach to this decision systematic, or intuitive?

Usually, we need to understand the kinematic function of the product. It is mostly intuitive.

What limitations do you see in the commercial use of compliant mechanisms?

Right kind of materials with flexibility and strength.

Reliability (related to the materials though).

Dynamic behavior (would need special attention in design)

Resistance of manufacturers to change their machines.

What is your vision of the future of compliant mechanisms?

At micro and nano scales, they are indispensable. At macro scale too, almost any product can use compliant mechanisms when material issues and economic factors related to their manufacturing are worked out. I firmly believe that ANY type of motion can be generated using compliant mechanisms.

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